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Reciprocity calibration in a compliant cylindrical tube

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THESIS

RECIPROCITY CALIBRATION IN A

COMPLIANT CYLINDRICAL TUBE

by

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June 1985

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20.(continued) 365 meters/second. The hydrophone voltage sensitivities obtained by the method, however, systematically differ by 1.5 decibels from those measured by comparison with a standard hydrophone; additional research will be required to resolve this discrepancy.

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Reciprocity Calibration in a Compliant Cylindrical Tube

by

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Lieutenant Commander, United States Navy
B.S., Cornell University, 1975

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MASTER OF SCIENCE IN PHYSICS

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June 1985

ABSTRACT

A new method for absolute calibration of electroacoustic transducers is described which permits low frequency reciprocity calibration in a test apparatus of small dimensions. The method takes advantage of the reduced wave speed in a cylindrical water column bounded by a compliant PVC tube to reduce the length of the standing wave to dimensions which can be easily handled in the laboratory.

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I. WHY COMPLIANT TUBE RECIPROCITY WORKS

A. ACOUSTIC CALIBRATION AND RECIPROCITY

There are two general classes of underwater acoustic transducer calibration: absolute, or primary, calibration, and comparison, or secondary, calibration. The latter presumes the availability of a sound field of known amplitude measured by a calibrated transducer, but absolute calibration can be performed using only voltage measurements and primary measurements of the test system environment in a sound field of unknown amplitude. Once the voltage sensitivity of a standard hydrophone has been established in a particular frequency range and environment by absolute calibration, it may be used as a reference for comparison calibration of other hydrophones and of projectors; this absolute calibration is most often done by the reciprocity method.

1. Fundamentals of Reciprocity Calibration

The reciprocity method for absolute calibration is based on the properties of linear, passive systems whose action can be described by the two-port equation (1.1), which relates the acoustic pressure and velocity (p,u) at a transducer's mechanical terminal and the voltage and current (E,I) at its electrical terminals by a symmetric or antisymmetric matrix of constant coefficients; such a system is called reciprocal.

$$\begin{pmatrix} p \\ E \end{pmatrix} = \begin{bmatrix} Z_m & \Phi \\ \pm\Phi & Z_E \end{bmatrix} \begin{pmatrix} u \\ I \end{pmatrix} \qquad (1.1)$$

Hunt [Ref. 1] derives this equation from first principles and shows how the matrix elements may be evaluated for common transducers. Foldy and Primakoff show [Ref. 2] that the short circuit transmitting current response S and the open circuit hydrophone voltage response M of a reciprocal transducer T are related by a constant factor

$$\frac{M_T}{S_T} = J = \frac{U_T}{P_H} \quad (1.2)$$

where J is called the reciprocity parameter and is characteristic of the test medium and its boundaries. Bobber has demonstrated [Ref. 3] that J is equivalent to the acoustic transfer admittance between an arbitrarily defined transmitting surface T generating a volume velocity U and an arbitrarily defined receiving surface H within the test environment exposed to an average pressure P, and exists as a function of the test medium and its boundaries for any arbitrary linear, passive, and reversible medium.

When two test transducers[1] are located at points in the medium where the pressure amplitudes are equal, the reciprocity parameter allows expression of the signal voltage of a test hydrophone H placed at one point as a function of the transmitter current response of a reversible transducer T placed at the other point and driven to create the sound field;

$$E_{TH} = M_H P_H = M_H S_T I_T \quad (1.3)$$

where I is the drive current input to T. If the sound field generated by T is then replaced by a field which is identical at the locations of T and H, but is generated by an separate projector P, the outputs of T and H in this new field will be related by equation (1.4). Combining this equation with (1.3) produces the calibration equation (1.5), which allows the computation of the test hydrophone's voltage sensitivity H directly from voltage measurements made in the three source-to-receiver configurations: T-to-H, P-to-H, and P-to-T.

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[1]To avoid confusion, the term test transducers will always be used when referring to both transducers used in the reciprocity calibration. The term reversible transducer, or the ANSI designator "T", will be used to refer to the reciprocal transducer used both as a hydrophone and as a projector during the calibration; test hydrophone, or "H" will designate the transducer used only as a hydrophone; and projector, or "P" will identify a third sound source used to create the sound field used in the test.

$$\frac{E_{PT}}{E_{PH}} = \frac{M_T P}{M_H P} = \frac{J\,S_T}{M_H} \tag{1.4}$$

$$M_H^2 = J\,\frac{E_{PH}\,E_{TH}}{E_{PT}\,I_T} \tag{1.5}$$

2. Reciprocity Test Geometries

Most reciprocity calibrations are made in one of the two earliest system geometries for which the reciprocity parameter was computed: free field [Ref. 4], or close-coupled [Ref. 5]. The techniques for carrying out these tests, and the limitations required to ensure the validity of the test are described by the ANSI standard for underwater calibration [Ref. 6]. The free field test geometry requires a volume of water large enough to permit spherical spreading of the acoustic waves undisturbed by boundary reflections. This implies tanks of dimensions greater than ten wavelengths (about 15 meters at 1 kilohertz) for underwater testing. Coupler reciprocity is limited by the requirement to encase the entire active surface of two test transducers in a rigid-walled cell of dimensions less than 1/10 of a wavelength; useful underwater low frequency transducers limited to such dimensions can be difficult to build.

The practice of reciprocity calibration is not, however, constrained to the two conventional geometries. Rudnick [Ref. 7] discusses three compact geometries with known reciprocity factors; Bobber's reference text on measurements [Ref. 8] describes several more. These unusual test environments extend the practice of reciprocity calibration beyond the limits of of the two conventional geometries. A summary of these methods is included in Table I; each of the reciprocity parameters listed is the quotient of an area characteristic of the system geometry, and of the specific acoustic impedance of the medium.

The compliant tube test system described in this paper adds another option to the array already available to the experimenter. It has particular value to the underwater acoustician because it

TABLE I

Some Reciprocity Calibration Systems

Geometry	Reciprocity Parameter	Reference
Free field	$\frac{2d\lambda}{\rho_0 c}$	4
Close-coupled	$\frac{2\pi ALf}{\rho_0 c^2}$	5
Plane-wave	$\frac{2A}{\rho_0 c}$	8
Cylindrical-wave	$\frac{2L\sqrt{d\lambda}}{\rho_0 c}$	8
Helmholtz resonator	$\frac{2\pi ALf}{\rho_0 c^2 Q}$	7
Waveguide, resonant plane wave	$\frac{\pi ALf}{\rho_0 c^2 Q}$	7

significantly lowers the frequency limit for underwater reciprocity calibration below the practical limits of the conventional geometries. Unlike rigid-tube methods, it can be accomplished within a convenient, inexpensive test cell, and although still limited by the requirement for accurate measurement of the system quality factor, does escape resonant reciprocity calibration's usual restriction to discrete frequencies. The "virtual rigid walls" created by the standing wave pressure antinodes, and in which the transducers are placed for the test, can be adjusted to any resonant length and frequency by simply raising or lowering the water level.

Our development of the compliant tube reciprocity parameter must begin from an understanding of wave motion in the water column,

and of the oscillatory expansion of the tube's circumference. From these equations, we will develop the energy balance of the oscillating system; this in turn will provide the result for the reciprocity parameter.

B. COMPLIANT TUBE WAVE EQUATION

1. Waves in the Water

Lighthill's development [Ref. 9] of the wave equation for a lossless fluid moving coaxially in a lossless tube of varying cross section includes the case of the compliant elastic tube in which our experiment is performed. The momentum and mass conservation equations for an inviscid, ideal fluid are

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial z} \tag{1.6}$$

$$\frac{\partial(\rho a)}{\partial t} + \frac{\partial}{\partial z}(\rho a u) = 0 \tag{1.7}$$

where p is the acoustic excess pressure, u the acoustic coaxial particle velocity, and a the local time-varying cross-sectional area of the tube, which varies slightly about its equilibrium value A. When fluid entropy is constant, both the local density ρ and the local cross section a may be expressed as functions of the acoustic pressure. (The latter relation is just the inverse of the function which relates pressure to cross section variations.) Discarding terms of second order and higher reduces these equations to

$$\rho_0\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial z} \tag{1.8}$$

$$\frac{\partial(\rho a)}{\partial t} = -\rho_0 A\frac{\partial u}{\partial z} \tag{1.9}$$

Taking the spatial derivative of (1.8) and the time derivative of (1.9), combining the results with the linearized equation of state $p = (\rho - \rho_0)c^2$ and discarding terms above first order gives a wave equation

$$\frac{\partial^2 p}{\partial z^2} = c^{-2}\frac{\partial^2 p}{\partial t^2} \tag{1.10}$$

where the wave speed c is defined by

$$c^{-2} = \rho_0\left(\frac{1}{\rho_0 A}\frac{\partial(\rho a)}{\partial p}\right)_0 = \rho_0\left(\frac{1}{\rho_0}\frac{\partial\rho}{\partial p}\bigg]_0 + \frac{1}{A}\frac{\partial a}{\partial p}\bigg]_0\right) \equiv \rho_0\Big(K + D\Big) \tag{1.11}$$

(The subscript "0" above implies evaluation of the derivative at the undeformed wall position and under adiabatic conditions.) The first term of equation (1.11) is the adiabatic compressibility or reciprocal bulk modulus K; if there were no dependence on cross section, this would reduce to the equation for the sound speed in the bulk medium. If the second term, called the distensibility D, is much larger than the adiabatic compressibility, the speed of sound waves in the tube will be determined by the characteristics of the wall rather than by those of the bulk fluid, and will be much slower. This in turn will reduce the size of the resonant tube required to operate at a given frequency.

The harmonic solution of equation (1.10) with a pressure release boundary at z=0 and a rigid boundary at z=L, and for frequencies below the cutoffs for azimuthal and radial modes, is

$$p(z,t) = P\sin(kz)\sin(\omega t) \tag{1.12}$$

with a corresponding velocity field

$$u(z,t) = \frac{P}{\rho_0 c} \cos(kz) \cos(\omega t) \tag{1.13}$$

The wave number k is limited by the boundary conditions to the discrete values

$$k = \frac{2\pi}{\lambda} = \frac{\pi(n + 1/2)}{L} \quad ; \quad n=0, 1, 2, 3, \ldots. \tag{1.14}$$

This sound field has associated with it both kinetic and potential energy density. The kinetic energy of axial water motion in a thin radial cross section of length dz is

$$dE_u = \frac{\rho_0 u^2}{2} A dz \tag{1.15}$$

The potential energy in the same section is found by considering the work done by the fluid as the tube boundaries expand:

$$dE_p = -\int_0^{\zeta} p \, dV = -\int_0^{\zeta} p \left\{ A dz \left. \frac{1}{A} \frac{da}{dp} \right]_0 - A \, dz \left. \frac{1}{\rho_0} \frac{\partial \rho}{\partial p} \right]_0 \right\} dp \tag{1.16}$$

$$= (K - D)\frac{p^2}{2} \; A dz \tag{1.17}$$

where ζ is a coordinate of the periodic motion.

2. Motion of the Wall

The distensibility can be calculated from the material properties of the tube wall and its geometry. In the case of a cylindrical tube which responds elastically to small excess stresses, the circumferential tensioning force component due to the pressure on a thin radial cross section of length dz is

$$F = 2Rdz \int_{-\pi/2}^{\pi/2} p \cos\theta \, d\theta = 4Rdz\, p \tag{1.18}$$

$$\varepsilon \equiv \frac{\delta a}{A} = \frac{F}{2hYdz} = \frac{2R}{hY} p \tag{1.19}$$

This tensioning force causes a strain ε defined by equation (1.19). Where p is small and a varies only slightly from its undisturbed value A, the distensibility is then

$$D \equiv \left.\frac{1}{A}\frac{da}{dp}\right]_0 = \frac{2R}{hY} \tag{1.20}$$

This stretching of the wall along its circumference has the characteristics of a damped, stiffness-controlled driven oscillator (neglecting longitudinal effects). The ratio of the driving pressure at any cross section and the circumferential strain velocity is the mechanical impedance of the cross-sectional ring treated as a damped oscillator of negligible mass with elastic constant Y and damping coefficient R(m) [Ref. 10:pp.10-12]

$$\varepsilon = \frac{2P \sin(kz)\sin(\omega t - \theta)}{\omega W} \tag{1.21}$$

$$W \cong \sqrt{R_m^2 + (Y/\omega)^2} \qquad \theta = \arctan\left(\frac{-Y}{\omega R_m}\right) \tag{1.22}$$

The polyvinyl chloride (PVC) tube used in this experiment is actually not elastic over any finite range of distortion, so the parameter Y is not Young's modulus; it is only a linear approximation to the plastic deformation that the PVC undergoes in harmonic motion. Within this linearization, the potential energy stored in a thin radial section of the wall as the tube is expanded by a small amount from its initial cross section can be found from the force-displacement integral

$$dE_W = \int_0^{\zeta} F \frac{\pi R}{2} \, d\varepsilon \;= Dp^2\Big]_{\zeta} \; Adz \tag{1.23}$$

with the force given by equation (1.18).

C. COMPLIANT TUBE RECIPROCITY PARAMETER

The arguments used by Garrett, et al., [Ref. 11] to derive the reciprocity parameter J for a rigid tube will also yield an expression for the reciprocity parameter of the free surface, compliant wall tube. As with the rigid tube, the solution depends on relating the energy content of the system E and the energy loss per cycle ΔE to the acoustic transfer admittance (reciprocity parameter) described by equation (1.2). When the ratio of energy content to energy loss rate is known in terms of J and of primary measurements, the resonance quality factor equation (1.24) (which can also be found from primary measurements) can be used to evaluate J.

$$Q = \frac{f}{f_h - f_l} = \frac{E}{\Delta E/2\pi} \tag{1.24}$$

1. System Energy Content and Losses

The compliant tube system stores energy both in the water column and in the tube wall. Kinetic energy of motion of the water pressurizes the water locally, which in turn stresses and expands the tube diameter. The energy balance exchanges between the three degrees of freedom are governed by the work equations for pressurization (equation (1.17)) and for expansion (equation (1.23)), and by the kinetic energy equation (1.15). Summing these equations gives the total energy in a thin cross section

$$dE = dE_u + dE_p + dE_w \;\; = A\,dz\left\{\frac{\rho_0 u^2}{2} + (K - D)\frac{p^2}{2} + Dp^2\right\} \tag{1.25}$$

$$= A dz\left\{\frac{\rho_0 u^2}{2} + \frac{p^2}{2}(K + D)\right\} = A dz\left\{\frac{\rho_0 u^2}{2} + \frac{p^2}{2\rho_0 c^2}\right\} \tag{1.26}$$

where equation (1.11) has been used to replace K and D with $\rho_0 c^2$. The sound field in the absence of attenuation is described by equations (1.12) and (1.13); substitution gives a form which can be integrated over the length of the water column

$$E = \int_0^L \left\{\frac{\rho_0}{2}\left(\frac{P}{\rho_0 c}\right)^2 \cos^2(kz)\cos^2(\omega t) + \frac{P^2}{2\rho_0 c^2}\sin^2(kz)\sin^2(\omega t)\right\} dz \tag{1.27}$$

$$= \frac{ALP^2}{4\rho_0 c^2} \tag{1.28}$$

This is identical to the result for a rigid resonant tube [Ref. 11].

In the steady state, the cyclic energy loss equals the work done by the driving transducer. If this transducer is located at a pressure antinode, pressure and velocity must be in phase at the transducer face (since the impedance to flow at a velocity node is infinite). The energy transferred to the system is the work done, which can be written as

$$\frac{\partial E}{\partial t} = \oint p\, \vec{u} \circ \hat{n}\, ds \;\; = P\,U \sin^2(\omega t) \tag{1.29}$$

where U is the volume velocity amplitude of the transducer surface. Integrating over one cycle gives

$$\Delta E = \frac{PU}{2f} \tag{1.30}$$

2. Reciprocity Parameter

Our calculations above have yielded both the system energy content and the system energy loss (actually, its throughput at steady state). The energy equation for Q (1.24) immediately produces

$$\frac{Q}{2\pi} = \frac{E}{\Delta E} = \frac{P}{U}\frac{ALf}{2\rho_0 c^2} \tag{1.31}$$

The ratio of volume velocity amplitude to pressure amplitude that appears in this result is the acoustic transfer admittance between pressure maxima (equation (1.2)), and must also be the reciprocity parameter for hydrophones positioned at separate maxima when the column is driven at resonance. Equation (1.32) follows; again, it is the same as the reciprocity parameter for the rigid tube.

$$J = \frac{\pi ALf}{\rho_0 c^2 Q} \tag{1.32}$$

The solution of equation (1.32) requires the experimental measurement of three resonance parameters: the resonance frequency f; the resonance quality factor Q; and the wavelength of the resonance standing wave, in order to compute the sound speed C. The accuracy of the value computed for J depends on our ability to measure these parameters accurately. The methods for doing this will be discussed in the next chapter.

In using equation (1.5) with the result derived above, we must ensure that the pressures and voltages implied are indeed the maximum amplitude values at the antinodes. The test transducers' output will be proportional to the average sound field over their active surfaces, which at its maximum will be less than that which would be generated by a uniform field at the maximum pressure amplitude P by the factor

$$\gamma_T = \frac{1}{A_T} \oint \cos k(z-z_m)\, ds \quad = \frac{\sin(kL_T/2)}{kL_T/2} \qquad (1.33)$$

Measured voltage outputs must be corrected by this factor before the results are used in the calibration equation when transducer dimensions are an appreciable fraction of a wavelength. For the LC-10's used in our experiments, this factor is 0.05 dB at 1kHz; for the LC-32's, it is 0.27 dB.

3. Limits of Derivation

The derivation of the compliant tube reciprocity parameter has been done under four important simplifying assumptions. To the degree that these approximations do not represent the real system, the results obtained by absolute calibration will be in error.

The first of these approximations is the use of the solutions to the lossless wave equations in computing the total energy in equation (1.28). The PVC wall does attenuate the sound wave, resulting in a resonance sound field which resembles that derived by Kinsler, Frey, Coppens, and Sanders [Ref. 10:pp.206-209]. Figure 1.1 shows the measured variation of the pressure amplitude with depth for the n=4 mode. The pressure amplitudes at separate maxima will therefore not be identical, as is required by our development, which assumes an infinite standing wave ratio.

A second approximation is the assumption of linear behavior for the polyvinyl chloride wall. In fact, PVC has no elastic region for strain, as was discussed in the derivation of the wall motion equation. The nonlinearity of the wall permits mode coupling into other resonance modes, particularly when two resonances have spatial pressure maxima near the same position and are related subharmonically. The result of such coupling when the column is driven at one frequency is to depress the amplitude of individual pressure maxima by an amount proportional to the degree of coupling at that position; again violating the requirement for equal pressure amplitudes at the two test positions.

Third, the reciprocity concept requires that the receiving transducer approximate an infinite mechanical impedance to the medium. While piezoceramics do meet this approximation very well, the soft mounting material used the the hydrophone body and gas bubbles on the hydrophone surface do not. Their presence could significantly distort the sound field in the vicinity of the transducer.

Finally, the projector used to drive the column into resonance does not produce a sound field identical to that generated by a small piezoelectric transducer suspended in the water column. The local sound field near the cylinder is some combination of radial modes which match the cylindrical boundary conditions to the overall plane wave, coupling the driving transducer to the standing wave system. The effects of this coupling factor are slightly frequency-dependent, and are not accounted for in this model.

Our measurements demonstrate that the simple model derived, despite these deficiencies, produces consistent results to within ±0.8 dB, but does not explain differences from a standard comparison calibration of up to 2.1 dB. The root-mean-square average difference is 1.5±0.4 dB for the range of hydrophone types and frequencies tested. A method and apparatus for performing this type of calibration experiment, and the results of our experiments, follow.

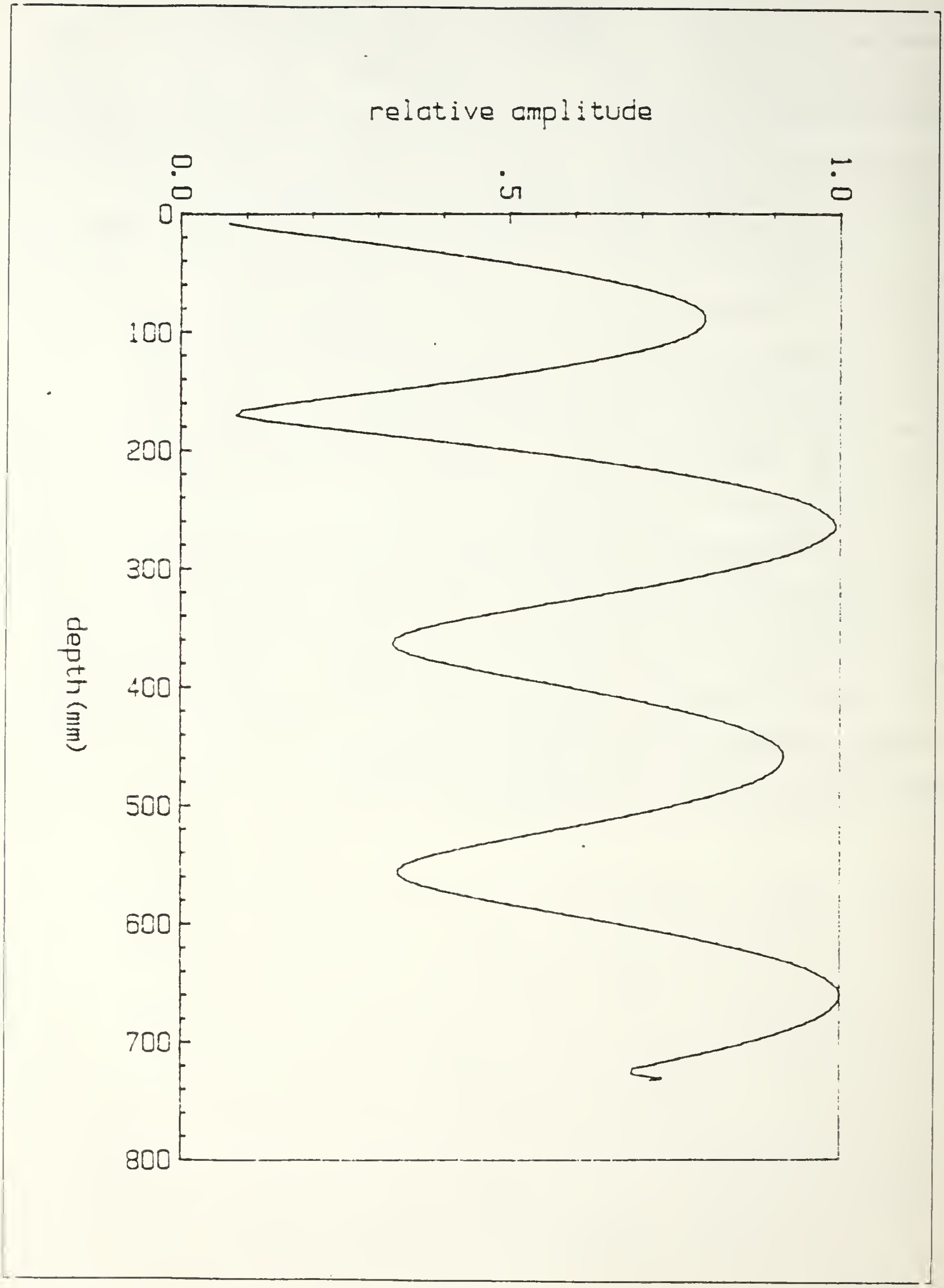

Figure 1.1 Pressure Amplitude Depth Profile (n=4)

II. COMPLIANT TUBE RECIPROCITY EXPERIMENTS

A. RESONANCE PARAMETER MEASUREMENT

The formula for the reciprocity parameter derived in the preceding section requires the accurate measurement of three resonance parameters: the resonance frequency, the sound speed at that frequency, and the resonance quality factor. Each of these measurements involves finding an extremum from a set of data samples, which will inevitably contain noise. The experimenter who attempts to resolve extrema from a discrete sample set by comparing measured signal outputs performs the discrete equivalent of differentiation, which enhances noise and increases net error in the result.

The solution to accurate, reproducible resonance parameter measurement which D. Conte and S. Garrett originally developed [Ref. 12] combines the high data rate of automated measurements with the power of curve fitting. The intuitive explanation of the effectiveness of this method is the human analogue; rather than take discrete measurements, experimenters instead "swing" the system slowly through the extremum, and let the eye interpolate the location of that point. The optimum automated processing analogue for this method is curve fitting to the minimum expansion of any function y(x) which will resolve extrema, the second order equation

$$y(x) = C_0 + C_1x + C_2x^2 \tag{2.1}$$

The three coefficients of this curve can be found for any set of three or more measurements; if more than three measurements are made, the nonlinear regression methods described by Bevington [Ref. 13] can be used to reduce the noise error in the measurement of the extremum, as long as the span of the sample set around the extremum is small enough

that equation (2.1) is a valid approximation. The regression equations for the three coefficients are algebraic, and are derived in Appendix B (equations (B.12), (B.13), and (B.14)). The location of the extremum (again from Appendix B) is displaced from the coordinate origin of the sample set by

$$x_m - x_0 = -C_1/2C_2 \tag{2.2}$$

In our application of this method to measurement of the resonance peak frequency , the sample set is composed of seven hydrophone output voltage amplitudes measured at equal frequency intervals; the sample set origin is shifted until the estimated peak frequency falls within one interval of the center frequency of the sample set. This is the peak frequency locating algorithm. Figure 2.1 is a example of this technique; the asterisks mark data points used to establish the coefficients for the curve and to compute the location of the maximum, and points marked with circles are discarded from the final fit because they are more than three steps from the extremum. The sound speed is found by sampling the pressure amplitude at regular intervals in depth from the surface, and again shifting the set used for curve fit until the estimated maximum or minimum is within one step of the center of the set. The positions thus located occur at quarter wavelength steps, and can be fit to

$$z_m = m\lambda/4 + z_0 \tag{2.3}$$

to obtain the wavelength; the sound speed is then just the product of the resonance peak frequency and the wavelength. This is the sound speed measurement algorithm.

The curve fit in frequency also yields a reduced-noise value for the peak amplitude at resonance, which is essential to accurate

measurement of the half-power frequencies required for the Q measurement algorithm (equation (1.24)). Once the half-power amplitude is known, the half-power frequencies can be found by sampling outward from the peak frequency until a pair of samples brackets this value at the minimum frequency interval permitted by the equipment (in our case, 1 Hz). The half power frequency is then calculated by linear interpolation.

The curve-fitting method can resolve extrema in noise to a degree far surpassing the eye integration method it was drawn from. It has the additional advantages of sound mathematical basis, speed, reproducibility, and independence from observer biases. It also has the considerable advantage of being easier on the observer. The method's main drawback is its bias toward finding the parabolic curve in any data, including pure noise; care must be taken in selecting stepsizes to ensure that the changes in the signal are not so small that they are overwhelmed by noise, and to ensure that the sample set span is not larger than the region about the extremum where a second order approximation is valid. The best method for checking new cases is graphical display of the data set and the curve for the operator approval.

B. DESCRIPTION OF EQUIPMENT

1. Control System (Figure 2.3)

The experiment is controlled by a venerable Hewlett Packard HP-85 laboratory computer with 32K memory extension, IEEE-488 bus controller, and appropriate ROM extensions. The program used is documented in Appendix C. Commands generated by the program over the data bus control the experiment's configuration changes during measurements through the two dual remote coaxial switches (Hewlett Packard HP 59307) and a Hewlett Packard HP 3421 Data Acquisition Control Unit. The latter unit is configured with two actuator relays and eight measurement channels (option 020). The two actuator relays control the operation of the reversing DC manipulator drive motor.

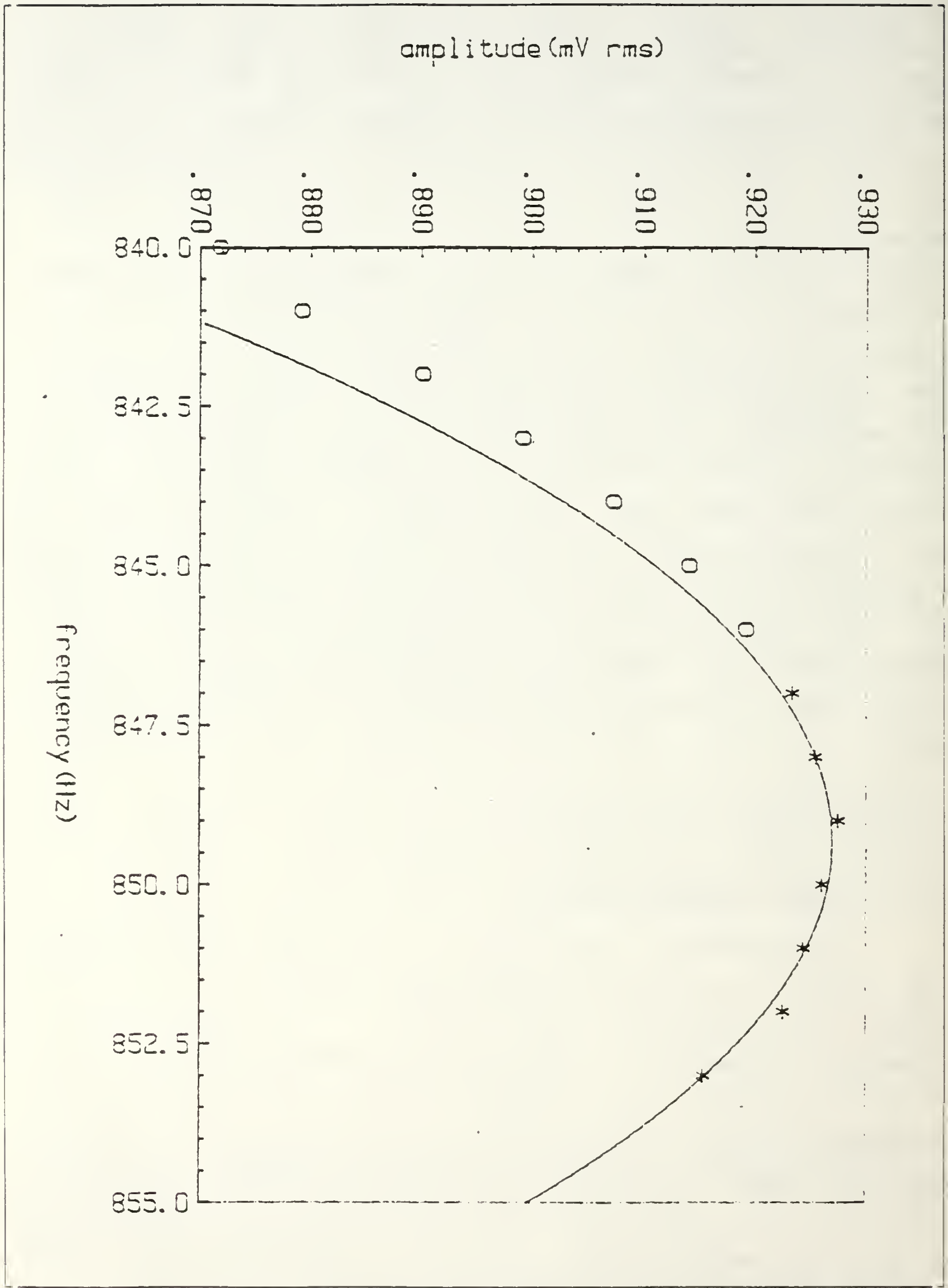

Figure 2.1 Parabolic Curve Fit in Frequency

Figure 2.2 ACTRE Test System

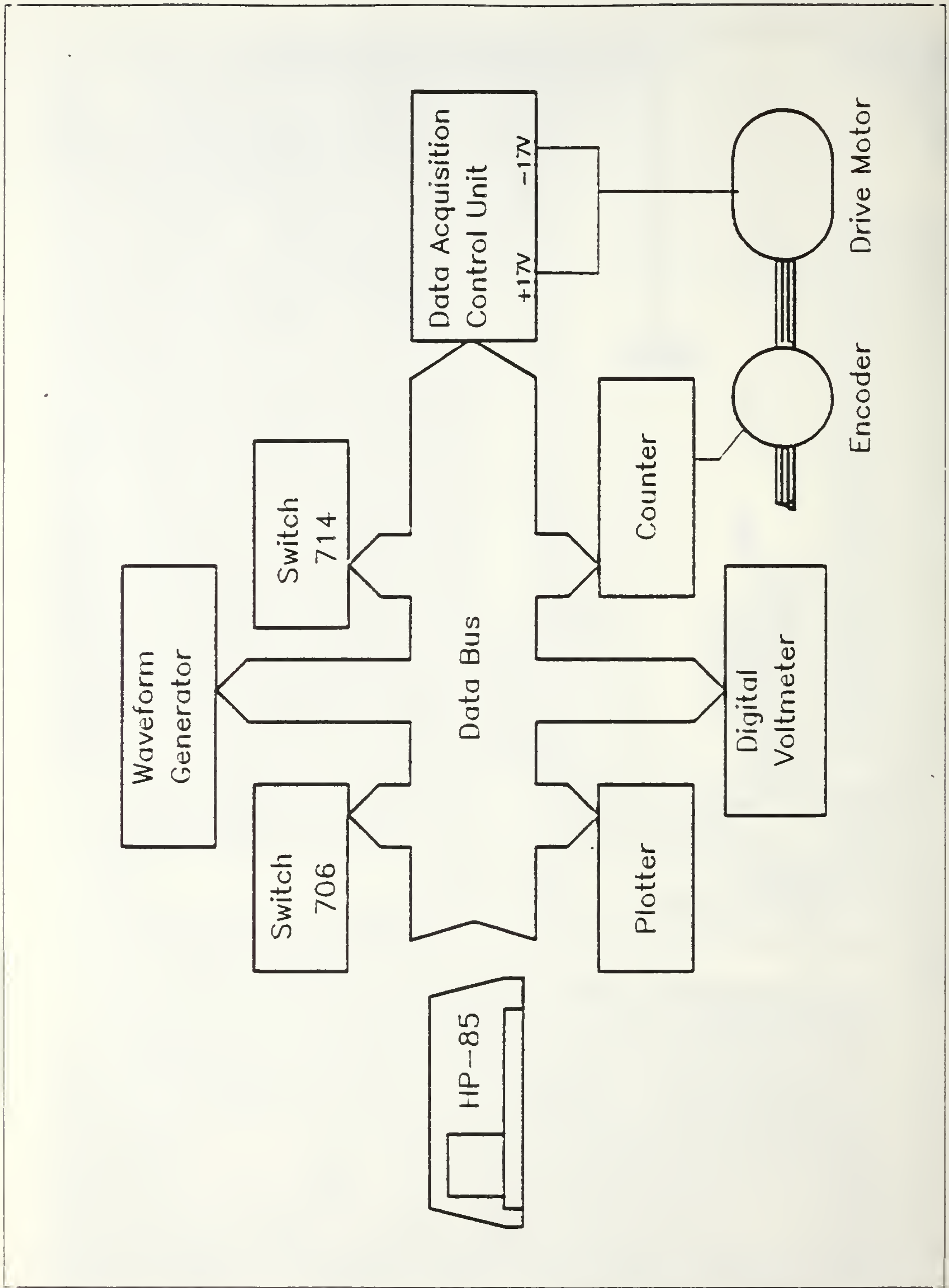

Figure 2.3 Control System Schematic

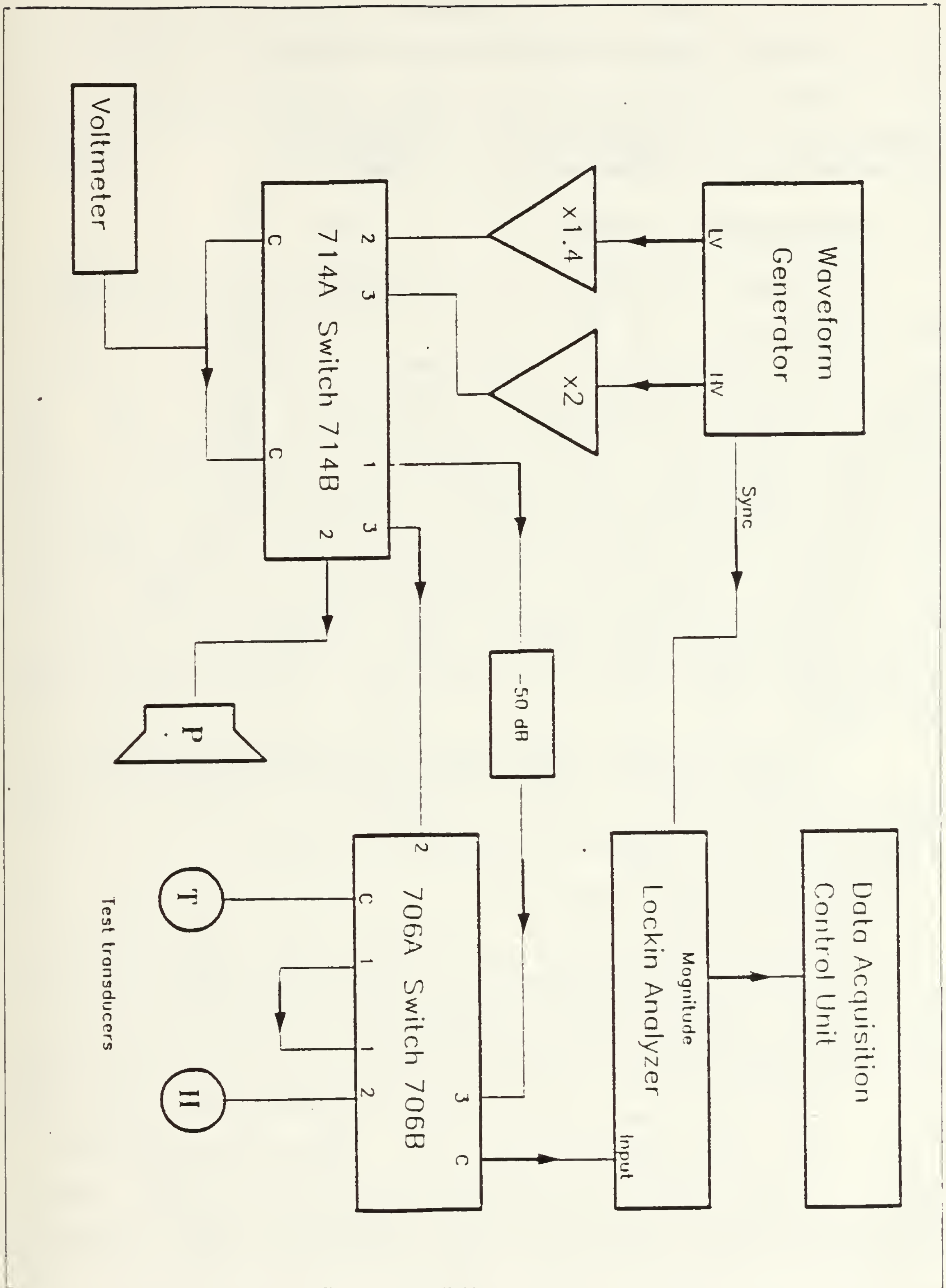

Figure 2.4 Transmitter/Receiver Schematic

The manipulator's screw drive, which is described below, also drives a Hewlett Packard HED 680 position encoder that increments a Hewlett Packard HP 5016 universal counter in totalizing mode. The changes in this totalized count provide (via the data bus) the program with a measurement of actual manipulator motion.

2. Transmitter (Figure 2.4)

A Hewlett Packard HP 3314 function generator provides a stable bus-controlled sine input signal at two voltage/current levels, and a synchronization signal at the selected frequency and constant voltage. The high voltage output is amplified and used to drive the piezoceramic transducer at rms voltages of 10 to 20 volts AC. The low-voltage, high-current demands of the USRD J11 projector [Ref. 14] are met by low-gain power amplification of the function generator's low voltage output. The transmit remote coaxial switch (714)[2] selects the signal source from these two options and feeds the signal to the reversible transducer switch (706A), to the J11 projector, or through a test attenuator which returns a known signal to the receiver input switch (706B).

A Hewlett Packard HP3478 digital multimeter, configured as a remotely controlled 5 1/2 digit AC voltmeter, is connected to the transmit signal line to measure the transmitting voltage.

3. Receiver (Figure 2.4)

The test transducers used in these experiments are: two Celesco LC-10 piezoceramic hydrophones (Figure 2.5), selected for their small size and good transmitting response; and a Celesco LC-32 piezoceramic hydrophone (Figure 2.6) of larger size. The voltage sensitivities of all three units were measured by comparison with a reference standard USRD H56 hydrophone [Ref. 14]. The results are listed in Table II. The LC-10's are mounted on 0.375 inch thinwall copper tubing; the LC-32 is mounted on 0.4375 inch tubing. Signal cables are

[2]The remote switches are identified here by their IEEE-488 bus address codes.

TABLE II

Comparison Calibration Results

(All values ± 0.8 decibels)

Frequency (Hz)	LC-10#2166 & 2m cable	LC-10#2338 & 9m cable	LC-32#85 & 11m cable
740	-206.5	-206.8	-212.3
860	-206.8	-207.3	-213.4
1000	-206.9	-208.8	-214.3

routed up the interior of the tubing to minimize effects on the sound field. The two test transducers are suspended from the manipulator platform. Their output is returned from the top of the manipulator assembly by two of three coaxial cables of the same length and measured capacitance. The third of these cables connects the test attenuator into the receiver input switch (706B), which makes all receive signal path wiring nearly equivalent. The reversible transducer switch (706A) selects either its receive or transmit lines; the receiver input switch (706B) selects the lockin analyzer input from the reversible transducer receive line, the test hydrophone, or the test attenuator.

The EG&G PAR model 5204 lockin analyzer filters out the components of the received signal which are in-phase and in-quadrature with the reference (synchronization) signal. Their Pythagorean sum is used to obtain the magnitude. The analyzer is typically operated with an integration time of 300 milliseconds, which corresponds to an equivalent noise bandwidth of 0.8 Hz; this causes the lockin analyzer to act as a very sharp filter synchronized to the transmitter signal. The analog output of the model 5204 is passed to a measurement channel of the HP 3421 for digitization.

4. Mechanical System

The tests are conducted in a 6-inch (154 mm) inside diameter Schedule 40 polyvinyl chloride tube mated to the active surface of a USRD J11 electrodynamic underwater projector [Ref. 14]. The tube

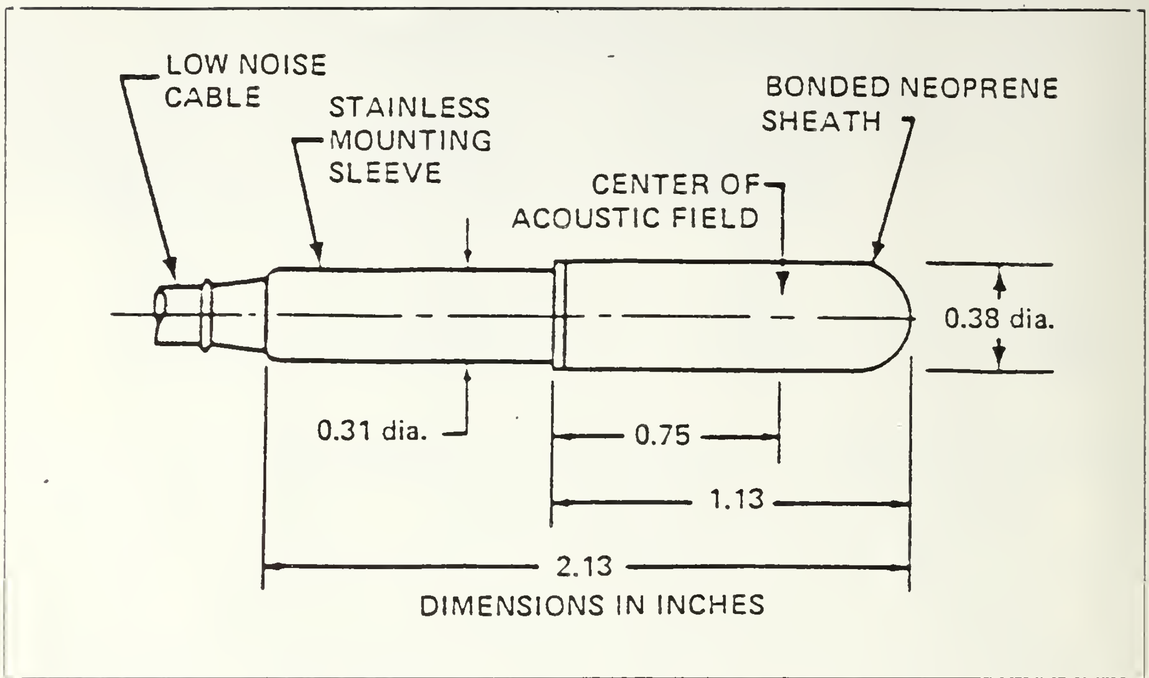

Figure 2.5 Celesco LC-10 Hydrophone
(Reprinted with permission of Celesco Industries, Inc.)

stands 1180 mm above the J11's active surface, and is filled to a depth of about 1 meter; its wall, which is smooth on the interior except for small regular extrusion marks, is 8 mm thick. The configuration resembles the USRD G40 calibrator used for comparison calibrations [Ref. 14]. (This system was originally constructed by Mills and Garrett for their work [Ref. 15] with fiber optic gradient hydrophones.) Equalization for the J11 driver is provided by air pressurization of the installed air bag, monitored with a water-filled U-tube manometer.

The test transducers are suspended on thinwall tubing supported on a rigid table which is raised and lowered on two one-inch rod tracks by a motor-driven screw drive; maximum range of motion is 800 mm. The drive controls were described in the paragraphs on the control system above.

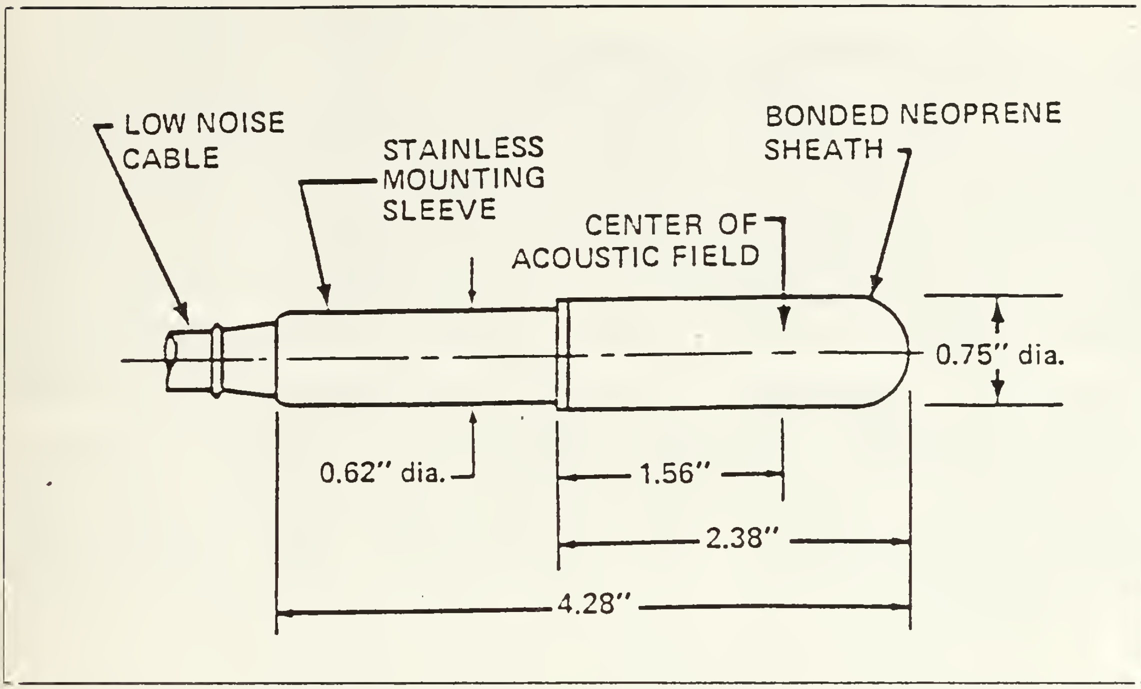

Figure 2.6 Celesco LC-32 Hydrophone
(Reprinted with permission of Celesco Industries, Inc.)

C. PROCEDURES FOR EXPERIMENT

1. Preparation

Before the test transducers are suspended in the water column, the experimenter must measure the reversible transducer's input capacitance, so that the transducer current can be computed from the transmitter input voltage and drive frequency. The active surface lengths of both hydrophones should also be measured for use in computing the transducer amplitude averaging factor (equation (1.33)). The test transducers are then suspended from the manipulator, wetted with a detergent solution, immersed in the water column, and brushed to remove bubbles from the active surface. If necessary, the tube's inner wall should also be brushed free of bubbles. The water column depth is measured with a meter stick.

2. Mode Selection

Two parameters are available to vary the resonant frequency of the water column at which the calibration is done: the water depth L and the mode number n (equation (2.4)). The procedure requires wavelengths much larger than the coaxial lengths of the transducers. In particular, the wavelength should be much longer than the coaxial length of the reversible transducer T to ensure that T's surface is entirely within the velocity node and feels little or no impressed pressure when T is transmitting. The wavelength should also be at least four times the length of the test hydrophone H. Practical experience has shown that calibration results are most accurate when T and H are positioned at two different pressure maxima of the n=3 or higher order resonance modes.

$$L = \frac{\lambda}{2}(n + 1/2) = \frac{c}{2f}(n + 1/2) \qquad (2.4)$$

3. Resonance Parameter Measurements

After positioning the test transducers at the approximate locations of the deepest and next deepest accessible spatial pressure maxima with similar pressure amplitudes, the operator uses the peak frequency measurement algorithm to find the resonance frequency f. The transducers are then withdrawn above the first pressure minimum.

One of the transducers is now used to measure the locations of maxima and minima in the standing wave pattern. Linear regression of this data gives the quarter wavelength, which in turn gives the sound speed.

Finally, the transducers are precisely repositioned at the maxima where the resonance frequency measurement was made. A precise measurement of the peak frequency and of the Q factor are made, completing the set of measurements needed to compute the reciprocity parameter from equation (1.32).

4. Calibration Measurements

Before making the final measurements, the experimenter switches the attenuated test signal into the receiver output to measure the net effects of cable losses, preamplifier gain drift, and deviations between the lockin analyzer's and the digital voltmeter's measurements. This correction is applied along with the amplitude averaging correction factors from equation (1.33) to the calibration voltage measurements that follow.

The transmitter is switched to the reversible transducer T, and the receiver to the test hydrophone H. The transducer-to-hydrophone output voltage E(TH) is measured, corrected, and recorded, as is the transmit voltage V(T). The latter is used with the capacitive admittance of T to compute the transmitter current I(T).

The transmitter is then switched to the projector, and the drive voltage adjusted to give a sound field of the same amplitude at H as was used in the previous step. The projector-to-hydrophone output voltage is recorded (it is equal to E(TH), within the limits of the projector drive adjustment error). The final calibration measurement is made with the receiver switched to T with the projector drive unchanged; the result is the projector-to-transducer output voltage E(PT).

These measurements complete the requirements to compute the test hydrophone voltage sensitivity from equation (1.5). The same set of measurements can be used to compute the reversible transducer's sensitivity using

$$M_T^2 = J\frac{E_{PT}E_{TH}}{E_{PH}I_T} \qquad (2.5)$$

The results for M are in volts per pascal; the customary units quoted are decibels re 1V/μPa, which is found by calculating

$$\mathcal{M} = 20 \log M - 120 \qquad (2.6)$$

5. Self-consistency Check

When both transducer can be used as reversible transducers, the results of the reciprocity calibration can be checked promptly by exchanging the transducers' roles in the calibration measurements. Repeat measurement of the resonance parameters and transducer repositioning is not required.

Unless the two transducers have identical nonlinear responses, this second set of readings will confirm the accuracy of the assumption of reciprocity. It will not, however, measure the error in computing the reciprocity parameter J, which must be estimated independently.

D. RESULTS OF EXPERIMENTS

1. Reciprocity Tests

Tests were run on the three transducers in all pair combinations at the three accessible modes: n= 3, 4, and 5. Modes below n=3 were inaccessible because the LC-10 transducers' transmitting response was too small for reliable measurements; modes above n=5 were attenuated into the 'tails' of the lower resonances, which obscured the half-power points needed to measure Q. Comparison of a number of reciprocity calibration test results showed reproducible results to within 0.8 decibels. However, the calibration results in Table IV disagree systematically with the values obtained for the same hydrophones by comparison with the USRD standard hydrophone (Table II) by 1.5 decibels (Table V).

2. Error Analysis

The self-consistency error quoted in Table IV was determined by reversing the electrical roles of the two transducers without changing their positions; the difference in computed results for the two measurements is the degree to which the system is not reciprocal. The estimated error is the combination of the self-consistency error with the error in measuring the reciprocity parameter, listed in Table III.

The primary source of self-consistency error is the difference in pressure amplitudes at the two maximum locations used, which we believe is caused by attenuation. By careful selection of modes and locations, we were able to reduce this error to 0.2 dB. Another lesser source of self-consistency error is the changing effect of the support tubing used for the transducers on the sound field as they are lowered into the water column. Insertion of the transducers and their supports into the water column displaces about 0.4 percent of the water column in volume, causing a similar change in the column depth and in the positions of maxima and minima. The change in the minima is the most significant error encountered in measuring the wavelength of the standing wave; because the cosine function is flat to first order, however, the effect on transducer positioning at maxima is negligibly small.

Compliant materials associated with the signal cables and the transducers appear to degrade the reciprocal nature of the geometry. This error is reduced to very low values by selection of transducer location and by eliminating compliant materials (signal cables, for example) in contact with the water.

Parameter measurement error is dominated by the apparent variation in the system quality factor over the length of the tube. An increase of 6-10 percent in the value of Q determined by the half-power frequency method was observed as the depth of the measurement was increased by one wavelength; our model for the compliant tube system does not account for such effects, and is therefore limited in the accuracy with which it predicts the reciprocity parameter to about 0.8 dB. This is the largest recognized source of measurement error in the compliant tube reciprocity method.

The systematically lower sensitivities measured by the reciprocity method relative to those measured by comparison with the H56 standard are not yet understood. This discrepancy may rise from the inadequacies of our model for the system energy balance, from the method used to measure Q, or even from technical difficulties with the comparison calibration.

3. Measurement of Wall Motion

Since sound speed can be measured directly, it is not necessary to attempt the difficult measurement of the actual elastic strain in the tube wall as part of the calibration process. However, the degree of correspondence of the actual strain behavior to the model derived in the first chapter is an important indication of the validity of our method.

The circumferential wall strain was measured by attaching constantan .250 inch strain gages [Ref. 16] to the exterior surface of the tube at the depths of some of the pressure maxima located by the test transducer. A second lockin analyzer used as the sensing element of a resistive DC bridge measured the magnitude and phase of the strain oscillations sensed by the strain gage; by comparing the output of the strain gage with the magnitude and phase of the pressure measured by the transducer at that depth, we computed the complex impedance (W, θ) of the wall ring (equation(1.21)). The results in Table VI agree in general with the measured sound speed in the tube. Also, the indicated damping phase effects are reasonably small, justifying our approximation for the wall potential energy computation of equation (1.23).

TABLE III

Resonance Parameter Measurements

Mode#	Frequency (Hz)	Wavelength (mm)	Sound Speed (m/s)	Q	J (nW/Pa^2)	Relative Error(dB)
3	725	498	366±6	14.4	20.7	0.5
4	864	404	355±3	17.5	22.2	0.5
5	1005	335	338±5	16.1	30.5	0.8

TABLE IV

Hydrophone Calibration Measurements

(All table entries are in decibels.)

Frequency (Hz)	LC-10 #2166 & 2m cable			LC-10#2338 & 9m cable			LC-32#85 & 11m cable		
	M	ΔMr	ΔM	M	ΔMr	ΔM	M	ΔMr	ΔM
725	-208.3	0.4	0.6	-208.5	0.4	0.6	-214.2	0.8	0.9
865	-207.9	0.4	0.6	-209.0	0.6	0.6	-213.3	0.6	0.8
1005	-209.0	0.4	0.9	-210.1	0.3	0.9	-215.3	0.1	0.8

RMS average total estimated error ΔM = 0.8 dB

M = Hydrophone voltage sensitivity (dB re 1V/μPa)
ΔMr = Self consistency error (dB)
ΔM = Total estimated error (dB)

TABLE V

Variations in Calibration Results

Reciprocity vs. comparison with USRD H56 standard (table II).
(All table entries are in decibels.)

Frequency (Hz)	LC-10 #2166 & 2m cable	LC-10 #2338 & 9m cable	LC-32 #85 & 11m cable	Average (RMS)
725	-1.8	-1.7	-1.9	-1.8
865	-1.1	-1.7	-1.1	-1.3
1005	-2.1	-1.3	-1.0	-1.5
Avg(RMS)	-1.7	-1.6	-1.3	-1.5±0.4

TABLE VI

Tube Wall Motion Measurements

Frequency (Hz)	Depth (wavelengths)	Impedance (10^9 Pa-s/ /degrees)	Elastic Constant (10^9 Pa)	Sound Speed(m/s) Equation (1.11)	Measured (Table III)
725	3/4	(2.7, -80)	2.6	330±30	365±6
868	3/4	(2.6, -76)	2.5	330±30	355±3
1005	5/4	(1.9, -82)	1.9	310±30	338±5

III. UTILITY OF COMPLIANT TUBE CALIBRATION

A. LIMITS OF COMPLIANT TUBE CALIBRATION

The compliant tube reciprocity method can be extended to low frequencies by simply increasing the length of the water column enclosed in the PVC tube, or by decreasing the wall thickness to diameter ratio (equations (1.11) and (1.20)). The practical lower frequency limit is the length necessary to support the n=3 standing wave, which from equation (2.4) is

$$f_{low} = \frac{7\ c}{4\ L} \qquad (3.1)$$

The upper frequency limit depends both on the onset of azimuthal modes, and on the increasing attenuation of the sound wave by the PVC wall. The former constraint breaks the plane wave symmetry when the frequency is greater than (0.586•L/R) times the fundamental longitudinal mode [Ref. 17]. The attenuation problem causes excessive variation of the measureable system quality factor with depth and reduces Q to the point where half power frequencies are obscured by adjacent resonances.

Test transducer geometry is restricted to shapes that are small enough in cross section that reflections from their lower surface do not significantly affect the standing wave. The length of the reversible transducer, as discussed in the procedure description, should be as short as possible consistent with adequate transmitting response. (A flat disk transducer might be more effective than the cylindrical LC-10 we used.) The test hydrophone can be much larger, if the transducer amplitude averaging correction is properly computed.

Accuracy of the method is primarily limited by the effects of the wall attenuation. A derivation which accounted for these effects, and

for the lesser effects of disturbances to the standing wave caused by the test transducers and their support tubing, could conceivably achieve much lower calibration uncertainities.

A significant advantage of the compliant tube method is the use of pressure antinodes as virtual rigid boundaries at which to locate the test transducers. Many of the difficulties associated with mounting a transducer in an real boundary which must have some compliance are thus avoided.

B. POTENTIAL APPLICATIONS

Two applications for the compliant tube system on a practical scale have been suggested to the author: a field/small lab calibrator, and a large, very low frequency calibrator.

The portability and flexibility of the test system used for compliant reciprocity recommends the method for general calibration use in small laboratories and in the field. The 1-meter PVC tube provides calibration capability in the 1 kHz range; a 2-meter, 10-inch diameter tube would be more versatile and could reach frequencies of 500 Hz. The manipulator assembly need not be as complicated or massive as the one used in our experiment; any system which can position the transducers within a few millimeters is adequate. Because the method involves resonance measurement methods as well as the techniques of reciprocity calibration, it may also be of interest for advanced instructional laboratories.

On a larger scale, a 10-meter, 30-inch diameter tube, which would fit upright in a two-story open bay, could reach frequencies below 100 Hz and calibrate units similar in size to the Navy's TR-155 transducer. If current interest in very low frequency underwater acoustics indicates a need for an alternative to the traveling-wave tube system described in [Ref. 8], compliant tube reciprocity may provide the answer at a very low cost.

There is also no reason we are aware of that the benefits of compliant waveguide usage should be limited to resonant calibration.

Construction of a compliant traveling wave tube calibrator with a non-reflecting termination or of a Helmholtz resonant calibrator using two compliant tubes should also be practical. The Helmholtz calibrator concept in particular has the potential of extending the range of accurate absolute calibration for the underwater acoustician to extremely low frequencies.

APPENDIX A
GLOSSARY

Subscripted variables in the text are represented using parentheses, due to word processor limitations.

A	Cross sectional area of the water column at rest.
A(T)	Active surface area of the transducer.
a	Instantaneous cross sectional area of the water column.
C(i)	Parabolic curve fit coefficients.
c	Sound speed in a compliant tube.
D	Distensibility of the boundary wall.
E(TH)	Transducer-driven, test hydrophone output voltage.
E(PH)	Projector-driven, test hydrophone output voltage.
E(PT)	Projector-driven, reversible transducer output voltage.
f	Resonance frequency.
H	The test hydrophone used only to receive during the reciprocity calibration.
h	Thickness of the tube wall.
I(T)	Transmitter current in reversible transducer T.
J	Reciprocity parameter, or acoustic transfer admittance, between two points.
K	Adiabatic compressibility of water.
k	Wave number at resonance = $2\pi/\lambda$.
L	Depth of the water column.
L(T)	Transducer's active length normal to the plane wave.
M	Hydrophone voltage sensitivity.
m	Number of quarter wavelengths below the water surface.
n	Resonance mode index.
n	Unit vector normal to surface element ds.
p	Acoustic wave excess pressure.
P	Pressure amplitude of the acoustic wave.
Q	Resonance quality factor.
R	Inner radius of the tube.

R(m)	Damping coefficient for tube wall vibrations.
S	Transmitting current response.
s	Surface area element.
T	The test transducer used both as a projector and as a hydrophone during the reciprocity calibration.
U	Volume velocity of the acoustic wave.
u	Particle velocity of the acoustic wave.
V	Volume element.
W	Complex mechanical impedance magnitude of the tube wall.
x(0)	Center coordinate of the data set used for curve fitting.
x(m)	Coordinate of extremum of the curve.
Y	Elastic coefficient for tube wall expansion.
y(i)	Sample set to be curve fit.
Z(E)	Transducer blocked electrical impedance.
Z(m)	Transducer open-circuit mechanical impedance.
z	Depth from surface of water column.
z(0)	Depth measurement offset.
z(m)	Depth of the mth pressure maximum/minimum.
δ	Sampling interval for curve fit sample set y(i).
ε	Areal strain in the wall. See equation (1.19).
γ	Length averaging correction factor.
θ	Complex mechanical impedance phase angle of the tube wall.
λ	Wavelength of the standing wave.
ρ	Instantaneous local water density.
ρ	Ambient water density.
Φ	Transformation factor.
χ^2	Sum of squared errors in a curve fit to data.
ω	Angular frequency at resonance.
ζ	Areal expansion coordinate.

APPENDIX B
PARABOLIC SMOOTHING ALGORITHM

The algebra of deriving formulas for the best choice of coefficients of a nonlinear equation, such that the sum of squared errors described by

$$\chi^2 = \sum \chi_i^2 = \sum \left[y(x_i) - y_i \right]^2 \qquad \text{(B.1)}$$

is minimized , is described by Bevington in [Ref. 13]. The minimum for the function defined by equation (B.1) is defined by the selection of coefficients which solve

$$\frac{\partial \chi^2}{\partial C} = 0 \qquad \text{(B.2)}$$

where C is any of the coefficients of the curve to be fit to the data.

The simplest function that will predict maxima and minima is the quadratic equation

$$y(x) = C_0 + C_1 x + C_2 x^2 \qquad \text{(B.3)}$$

The single extremum of this curve occurs at

$$x_m - x_0 = -C_1/2C_2 \qquad \text{(B.4)}$$

with respect to the coordinate origin located at x. Let the sample set be seven measurements of the function y sampled at regular intervals δ

$$y_i = y(x_0 + i\delta) \;;\; i = -3, -2, -1, 0, +1, +2, +3. \tag{B.5}$$

Evaluating the best fit function's partial derivatives with respect to the three parameters for such a sampled data set gives equations (B.6) thru (B.11); summing and cancelling yield equations (B.12), (B.13), and (B.14). These analytic results can then be used with equations (B.3) and (B.4) to obtain the location of the maximum and its amplitude, or the smoothed value for the amplitude at any location.

$$\chi_{-3} = 9\delta^2 C_2 - 3\delta C_1 + C_0 - y_{-3} \tag{B.6}$$

$$\chi_{-2} = 4\delta^2 C_2 - 2\delta C_1 + C_0 - y_{-2} \tag{B.7}$$

$$\chi_{-1} = \delta^2 C_2 - \delta C_1 + C_0 - y_{-1} \tag{B.8}$$

$$\chi_0 = C_0 - y_0 \tag{B.9}$$

$$\chi_{+1} = \delta^2 C_2 + \delta C_1 + C_0 - y_{+1} \tag{B.10}$$

$$\chi_{+2} = 4\delta^2 C_2 + 2\delta C_1 + C_0 - y_{+2}$$

$$\chi_{+3} = 9\delta^2 C_2 + 3\delta C_1 + C_0 - y_{+3} \tag{B.11}$$

$$84\delta^2 C_2 = 5(y_{+3} + y_{-3}) - 3(y_{+1} + y_{-1} - 4y_0\ ) \tag{B.12}$$

$$28\delta C_1 = 3(y_{+3} - y_{-3}) + 2(y_{+2} - y_{-2}) + (y_{+1} - y_{-1}) \tag{B.13}$$

$$21C_0 = 7y_0 + 6(y_{+1} + y_{-1}) + 3(y_{+2} + y_{-2}) - 2(y_{+3} + y_{-3}) \tag{B.14}$$

APPENDIX C

ACTRE: HP-85 BASIC PROGRAM FOR RECIPROCITY EXPERIMENTS

A. WHAT THE PROGRAM DOES

The Automated, Compliant Tube Reciprocity Experiment (ACTRE) program provides the operator with a menu of soft key controlled "tools" for resonance parameter and calibration measurements. Its design was based on the need for maximum flexibility, rather than maximum unattended operation.

All of the measurement "tools" are subroutines called from the HP-85 function keys by the operator. The major procedures are: the peak frequency location algorithm (KEY 1); the spatial optimum location algorithm, which also computes wavelength and sound speed (KEY 2); the Q measurement algorithm (KEY 5); and the reciprocity calibration measurement sequence (KEY 7). Supporting procedures provide the actual control statements for remote switching, function generator setup, manipulator positioning of the hydrophones, receiver output measurement, and graphics output. Any procedure may be terminated by calling the process clear sequence (KEY 8). Comments on the detailed structure of the program are included with the source code.

The program was developed to fit the demands of the experimental apparatus, the experimenter, and the research goals of this work as well as the limits of the host computer permitted. Time and core memory constraints severely limited efforts to make the program friendly or accessible to the uninformed.

B. TEST EQUIPMENT BUS CONNECTIONS

The code is designed to use the IEEE-488 bus-controlled test equipment described below. All of the primary measurements are made with bus-controlled equipment, except for the hydrophone output voltage measurement by the EG&G 5204 lockin analyzer, whose output signal must be converted using the HP 3421 D/A unit.

Bus assignment numbers used in the program:

705	HP7470 hardcopy plotter.
706	HP59307A remote controlled switch: A switch: reversible transducer; B switch: receiver input.
707	HP 3314 function generator.
709	HP 3421 Data Acquisition/Control Unit, with Opt 020 board in slot 0. Channel assignments: 0: Manipulator motor drive up actuator 1: Manipulator motor drive down actuator 5: 5204 lockin analyzer magnitude signal.
714	HP 59307A remote controlled switch (transmit side).
720	HP 5316 Frequency counter, in count totalize mode.
723	HP 3478 digital multimeter, configured as an AC voltmeter.

C. VARIABLE ASSIGNMENTS

1. Defined Functions

FNH(X1)	Length averaging correction function (equation (1.33)).
FNK(K0)	Cycles K0 through the indices 1,2,3. Used in plot scaling algorithm.
FNL(X0)	Returns decibel value of X0 = 20 log(X0).
FNM(X0)	Returns voltage sensitivity in dB re 1V/µPa (equation(2.6)).
FNR(X0)	Returns value of X0 rounded to three significant places; required for compatibility with HP3314 function generator amplitude command.

2. Variables

A(7)	Amplitude sampling array, used for curve fitting algorithms.
A2	Amplitude ratio of hydrophone output voltage to transmitter input voltage. Measured by the Amplitude Read procedure.
A4	Half power amplitude in Q measurement procedure.
A5	Lockin analyzer output signal to D/A unit (709) channel 5; ranges from 0-1 V to indicate 0-full scale magnitude reading.
A7	Resonance peak amplitude, computed from curve fit.
A8	Preceding measurement storage--in Q measurement procedure.
B(3)	Plot scaling parameter array
B1-B9	Plot parameters
C1-C5	Sums used in wavelength measurement least-squares procedure [Ref. 13]. C1: Sum of N9. C2: Sum of N9*N9. C3: Sum of L9. C4: Sum of L9*N9. C5: Sum of L9*L9.
C6	The quantity Δ in the least-squares fit.
C7	Resonance sound speed (m/s).
C8	Error estimate for C7 (m/s).
D1	Water column depth(mm)
D2	Water column cross section (mm^2)
D3	Water column volume(m^3)
D5	Length of T (mm).
D6	Length of H (mm).

E1	E(PT): Output voltage of T , P driven (V).
E2	E(PH): Output voltage of H , P driven (V).
E3	E(TH): Output voltage of H , T driven (V).

All frequencies are in hertz(Hz).

F0	Center frequency of sample set.
F1	First peak detection / Lower 1/2 power point.
F2	Second peak detection / Upper 1/2 power point.
F3	Peak frequency estimate.
F4	Lower search boundary.
F5	Upper search boundary.
F6	Drive frequency; argument passed to Amplitude Read Setup procedure.
F7	Resonance peak frequency.
F8	Error estimate for F7.
F9	Stepsize.

G2	Receiver preamplifier gain.
G5	Lockin analyzer output expand setting.
G7	Calibration attenuator value.
G8	Drive boost factor for preamp calibration test in Calibration routine.

H1	Length averaging correction factor for T.
H2	Length averaging correction factor for H.

I0	General use
I3	Size of plot files X(), Y().
I4	Selection index for Operator Input procedure.
I5	Number of time constants T5 to delay before measurements.
I8	Select index for Switching procedure.
I9	Wavelength measurements count.
J3	Reversible transducer(T) transmit current (A).
J7	Reciprocity factor ($V*A/Pa^2$).
K0	Water density (kg/m^3).
K3	Plot scaling array index.
L9	Pressure maximum/minimum position (m).
M1	Hydrophone voltage sensitivity of T (V/Pa).
M2	Hydrophone voltage sensitivity of H (V/Pa).
N0-N2	Position counts; used to compute manipulator motion.
N9	Number of 1/4 wavelengths from surface corresponding to L9.
Q7	Measured quality factor of resonance.
R0	Position encoder count ratio for down motion (counts/mm).
R1	Manipulator drive rate (counts/sec), down motion.
R2	Manipulator drive rate (mm/sec), down motion.
R3	Allowed projector drive adjust error.

R4	Allowed peak frequency detection range.
R5	Allowed min/max detection range.
R7	Q measurement coarse stepsize factor.
R8	Manipulator up/down motion rate ratio.

The S variables are all control flags/indices.

S0	General use.
S1	Read enable flag.
S2	Manipulator motion stop flag.
S3	Plot option enable flag.
S4	Fast display refresh flag.
S5	Drive voltage select index: 0: use J11 projector drive voltage V4; 1: use piezoceramic drive voltage V3.
S6	Automatic drive voltage control enable flag.
S7	Resonance peak detection index.
S9	Plot execute flag and abscissa select index.

All times are in milliseconds.

T2	Manipulator motion time adjust.
T5	Lockin analyzer time constant.
T7	Additional delay time before measurement.
T8	Size of additional delay T7 to be used when required.

U0	Curve fit amplitude at center of sample set.
U1	Curve fit slope*stepsize.
U2	Curve fit curvature *(stepsize)^2.
U9	Stepsize used in last curve fit (for plot procedure).

All voltages are in volts(V)rms, except where indicated.

V1	Transmitter input voltage.
V2	Hydrophone output voltage.
V3	Piezoceramic drive voltage(Vp-p).
V4	J11 projector drive voltage(Vp-p).
V5	Lockin analyzer fullscale setting; input as milli-volts,and converted to volts.
V6	Function generator drive voltage (Vp-p).
V7	Transmitter input voltage at resonance.
V8	Curve fit amplitude at F7, returned by 5-point Voltage Measurement procedure.

W0-W3	General use working variables.
X(50)	Abscissa plot storage array (Hz or mm).
Y(50)	Ordinate plot storage array (mV rms).
X0	Reference x-coordinate for curve fit plot (Hz or mm).

All variables beginning with "Z" are in millimeters(mm).

Z(7)	Sampling positions for λ Measurement procedure.
Z0	Manipulator table position.
Z2	Estimated position of pressure minimum/maximum.
Z4	Position of center of sample data set/ operator-ordered position to move to.
Z8	Measured stepsize in λ Measurement procedure.
Z9	Ordered stepsize.

3. Character String Variables.

A$(128)	Title; used to identify printout and plots.
M$(20)	Code identifier.
S$(5)	Remote switch position identifier.
W$(32)	General character input.

D. SOURCE CODE

```
1000 ! program actre-7
1010 ! Automated, Compliant Tube Reciprocity Experiment
1020 ! M.B. Johnson, Dec 84
1030 !
1040 PRINTER IS 2 @ OPTION BASE 1@ DEG
1050 DIM A$[128],H$[5],W$[32],S$[5]
1060 A$="ACTRE-7 mod 8      " @ CLEAR @ DISP A$
1070 ! Functions
1080 DEF FNH(X1) = X1/SIN(RTD(X1))
1090 DEF FNK(K1) = K1 MOD 3+1
1100 DEF FNL(X1) = 20*LGT(X1)
1110 DEF FNM(X1) = FNL(X1)-120
1120 DEF FNR(X1) ! rounds to 3 significant figures for HP3314
1130 W1=.01
1140 ! begin loop
1150 IF IP(X1)<1 THEN X1=X1*1000 @ W1=W1/1000 @ GOTO 1140
1160 IF IP(X1)>9 THEN X1=X1/10 @ W1=W1*10 @ GOTO 1140
1170 ! end loop
1180 FNR=W1*IP(X1*100+.5)
1190 FN END
1200 ! end: functions
1210 ! Variable initialization
1220 REAL A(7),A2,A4,A5,A7,A8,C1,C2,C3,C4,C5,C6,C7,C8,D1,D2
1230 REAL D3,E1,E2,E3,F0,F1,F2,F3,F7,G2,J3,J4,J7,K0,L9,M1,M2
1240 REAL N0,N1,N2,U0,U1,U2,V1,V2,V8,Y3,Z(7),Z0,Z2,Z3,Z4,Z8
1250 SHORT B(3),B1,B2,B3,B4,B5,B6,F4,F5,F6,F8,F9,G5,G7,G8
1260 SHORT R0,R1,R2,R3,R4,R5,R7,R8,T2,T5,T7,T8,U9,V3,V4,V5,V6,V7
1270 SHORT X(50),X0,Y(50),Z9
1280 INTEGER B8,B9,I0,I3,I4,I5,I8,I9,K3,K9,N3,N4,N9
1290 INTEGER S0,S1,S2,S3,S4,S5,S6,S7,S9
1300 ! initial values
1310 S1,S2,S6=1
1320 S3,S4,S9=0
1330 D2=PI*154*154/4 ! mm^2
1340 G2=1 @ G7=289.689 @ G8=30
1350 R0=512.5 @ R1=600 @ R2=.6/R0 @ R8=1 @ T2=188 ! move consts
1360 R3=.01 ! P adjust error
1370 R4,R5=1.01 ! peak detect error
1380 I4=6 @ GOSUB 2060
1390 I4=8 @ Z0=0 @ GOSUB 2060 ! position input
1400 I4=2 @ GOSUB 2060 ! depth,temperature
1410 R7=120 ! @ outstep ratio
1420 B(1),B(2)=2 @ B(3)=2.5 ! plot scaling parameters
1430 I5=5 @ T8=0 ! read delay factors
1440 K0=998.2 ! kg/m^3 water density
```

```
1450 ! begin: equipment setup====================================
1460 OUTPUT 709 ;"RS" ! clear A/D unit
1470 OUTPUT 707 ;"PR" ! clear 3314 fcn generator
1480 OUTPUT 723 ;"H2" ! xmit voltmeter
1490 OUTPUT 707 ;"AP10MV"
1500 OUTPUT 709 ;"F1R0RA0Z1N5LS5;T1" ! a/d receiver output
1510 OUTPUT 720 ;"FN12" ! position counter
1520 OUTPUT 709 ;"CLS5"
1530 I4=1 @ GOSUB 2060 ! LIA parameters
1540 ! end: equipment setup======================================
1550 ! begin: fresh slate for processing =======================
1560 I3,I9,N9,N4=0 ! plot file &wl/4 file sizes ,wl/4 count
1570 C1,C2,C3,C4,C5,C6=0 ! wavelength sums
1580 F7,F8,C7,C8,Q7,V6=0
1590 M1,M2=1000000 ! 0 dB re 1V/uPa
1600 V4=.0001 @ V3=10 @ T7=0
1610 S6=1 ! ADC on
1620 I8=1 @ GOSUB 8120 ! switch
1630 GOSUB 1800 ! set main menu
1640 ! end: fresh slate for processing==========================
1650 ! begin:processing stage====================================
1660 ! hold here for operator menu selection
1670 CLEAR
1680 DISP USING 8590 ; A$,F7,F8,C7,C8,Q7,FNM(M1),FNM(M2)
1690 IF S3 THEN DISP "plot on    ";ELSE DISP "plot off    ";
1700 IF S6 THEN DISP "ADC on" ELSE DISP "ADC off"
1710 DISP S$;"          Z0=";Z0
1720 KEY LABEL
1730 FOR I7=1 TO 49999
1740 IF S4 THEN 1760 ! fast refresh on return from key routine
1750 NEXT I7
1760 S4=0
1770 GOTO 1660
1780 ! end: processing stage====================================
```

```
1790 ! ==========MENUS=========================================
1800 ! begin: main menu========================================
1810 ON KEY# 1,"Fn" GOSUB 2650
1820 ON KEY# 2,CHR$(11) GOSUB 4150
1830 ON KEY# 3,"move" GOSUB 7990
1840 ON KEY# 4,"opr" GOSUB 2060
1850 ON KEY# 5,"Q" GOSUB 3380
1860 ON KEY# 6,"a/pt" GOSUB 8120
1870 ON KEY# 7,"CAL" GOSUB 5190
1880 ON KEY# 8,"clear" GOTO 1930
1890 S4=1 ! fast refresh
1900 RETURN
1910 ! end:main menu=========================================
1920 ! begin: clear slate menu
1930 !  provides exit/refresh processing
1940 OFF TIMER# 1 @ OFF TIMER# 2
1950 OUTPUT 709 ;"OPN0" @ OUTPUT 709 ;"OPN1"
1960 S1,S2=1 ! flag reset
1970 I3,S3,S9=0 ! plot dump
1980 ON KEY# 1,"main" GOSUB 1800
1990 ON KEY# 5,"wipe" GOTO 1550
2000 ON KEY# 6,"quit" GOTO 8840
2010 PRINT "OPERATOR CLEAR/RESET"
2020 S4=1 ! fast refresh
2030 GOTO 1650 ! enter processing stage
2040 ! end: clear menu=======================================
```

```
2050 ! ======PROCEDURES=========================================
2060 ! begin: operator input procedure (HP-HUMAN bus)===========
2070 IF I4=0 THEN 2080 ELSE 2130
2080 ! menu display
2090 CLEAR @ DISP USING 8600 @ DISP USING 8650
2100 INPUT W0
2110 IF W0>9 THEN Z0=W0 @ W0=0 ELSE I4=W0
2120 IF I4=0 THEN 2630 ! return to main menu
2130 ON I4 GOTO 2140,2200,2260,2310,2360,2400,2530,2590,2440
2140 ! 5204 LIA settings(i4=1)
2150 DISP "LIA fullscale(mV),time constant(ms),expand";
2160 INPUT V5,T5,G5@ V5=V5/(1000*G5)
2170 DISP "delay: # time consts,extra time(ms)";@ INPUT I5,T9
2180 PRINT USING 8610 ; 1000*V5,G5,T5,I5,T9
2190 GOTO 2630
2200 ! water depth,temp(i4=2)
2210 DISP "column depth(mm),temperature(C)";@ INPUT D1,W1
2220 D3=D1*D2/10^9
2230 PRINT USING 8620 ; D1,D3
2240 PRINT USING 8640 ; W1
2250 GOTO 2630
2260 ! drive voltages(i4=3)
2270 DISP "drive for P/T";V4;"/";V3;@ INPUT W$
2280 IF LEN(W$)>0 THEN V4=VAL(W$) @ V3=VAL(W$[POS(W$,"/")+1])
2290 PRINT "P drive:";V4;"V" @ PRINT "T drive:";V3;"V"
2300 GOTO 2630
2310 ! comments (I4=4)
2320 DISP "comments"
2330 INPUT W$
2340 IF LEN(W$)>0 THEN PRINT "#";W$ @ GOTO 2330 ELSE 2350
2350 GOTO 2630
2360 ! various constants(I4=5)
2370 CLEAR @ DISP "enter new values,then CONTINUE" @ PAUSE
2380 COPY
2390 GOTO 2630
```

```
2400 ! title (I4=6)
2410 A$=A$[1,18]
2420 DISP "date";@ INPUT W$@ A$=A$&W$ @ GOSUB 8070
2430 DISP "run #" @ INPUT W$@ A$=A$&W$ @ GOSUB 8070
2440 ! transducer chars only(i4=9)
2450 A$=A$[1,64]
2460 H$="T is:" @ DISP H$;@ INPUT W$@ A$=A$&H$&W$ @ GOSUB 8070
2470 DISP "T active length(mm),capacitance(pF)";@ INPUT D5,Y3
2480 H$="H is:" @ DISP H$;@ INPUT W$@ A$=A$&H$&W$
2490 DISP "H active length(mm)";@ INPUT D6
2500 PRINT USING 8630 ; A$,D5,Y3,D6
2510 Y3=Y3/10^12 @ D5=D5/1000 @ D6=D6/1000 ! SI conversions
2520 GOTO 2630
2530 ! plot enable/disable(i4=7)
2540 S3=NOT S3 @ I3=0
2550 IF S3 THEN 2560 ELSE 2630
2560 PLOTTER IS 705
2570 LIMIT 32,232,30,180 @ LOCATE 22,122,27,97 @ PEN 0
2580 GOTO 2630
2590 ! position(i4=8)
2600 DISP "position=";Z0;@ INPUT W$
2610 IF LEN(W$)>0 THEN Z0=VAL(W$)
2620 GOTO 2630
2630 I4=0 @ S4=1 @ RETURN
2640 ! end: operator input procedure==========================
```

```
2650 ! begin: peak frequency measurement procedure============
2660 PRINT USING 8460 ; A$ ! title
2670 CLEAR @ DISP "peak frequency measurement"
2680 DISP "estimate,search range,stepsize";@ INPUT F7,W0,F9
2690 F4=IP(F7-W0)
2700 F5=CEIL(F7+W0)
2710 ! documentation
2720 PRINT USING 8470 ; TIME,F7,W0,F9
2730 ! warmup reading
2740 IF S5 THEN V6=V3 ELSE V6=V4
2750 F6=F7 @ T7=T8 @ GOSUB 6990 ! xmtr on ,long delay
2760 GOSUB 7310 ! warmup read
2770 IF S3 THEN S9=1 @ GOSUB 5770 ! begin plot of a vs f
2780 ! begin :initialize sampling array
2790 F6=F4-3*F9 @ GOSUB 6990
2800 FOR I2=1 TO 7
2810 GOSUB 7310 ! read amplitude A2
2820 IF I2<7 THEN F6=F6+F9 @ GOSUB 6990 ! xmtr on next freq step
2830 A(I2)=A2
2840 NEXT I2
2850 ! end :fill sample array
2860 ! begin:resonance search
2870 S7,F1,F2,F7=0 ! peak detect flag and detection storage
2880 FOR F0=F4 TO F5 STEP F9
2890 ! f0 is the freq at the center of the sample data set
2900 F6=F0+4*F9 @ GOSUB 6990 ! xmtr on next read freq
2910 ! curvature at f0
2920 U2=(5*(A(7)+A(1))-3*(A(5)+A(3))-4*A(4))/84
2930 DISP USING 8480 ; F0,U2
2940 IF U2<0 THEN 2950 ELSE 3120
2950 ! slope at f0
2960 U1=(3*(A(7)-A(1))+2*(A(6)-A(2))+(A(5)-A(3)))/28
2970 !  peak frequency
2980 F3=F0-F9*U1/(2*U2)
2990 DISP USING 8490 ; F3
3000 IF ABS(F3-F0)<F9*R4 THEN 3010 ELSE 3120
```

```
3010 ! peak detected at center of sample array
3020 !  peak amplitude
3030 U0=(7*A(4)+6*(A(3)+A(5))+3*(A(2)+A(6))-2*(A(7)+A(1)))/21
3040 A7=U0-U1*U1/(4*U2)
3050 S7=S7+1 @ V7=V1
3060 IF S5 THEN V3=V6 ELSE V4=V6
3070 IF S7=1 THEN F1=F3 ELSE F2=F3
3080 PRINT USING 8500 ; F3,1000*A7*V1,1000*U2,1000*V1
3090 U9=F9 @ X0=F0
3100 GOTO 3160
3110 ! end:peak detected block
3120 ! begin:peak not detected block
3130 S7=0 ! unset peak detect flag
3140 ! end: peak not detected
3150 ! end:tests at F0
3160 DISP
3170 IF S7<2 THEN 3180 ELSE 3240 ! end search on two detects
3180 ! push down sampling array
3190 FOR I0=1 TO 6
3200 A(I0)=A(I0+1)
3210 NEXT I0
3220 GOSUB 7310 @ A(7)=A2
3230 NEXT F0
3240 ! end search
3250 IF S3 THEN GOSUB 5830 ! show plot
3260 IF S7<2 THEN COPY @ GOTO 3270 ELSE 3310
3270 IF F1=0 THEN PRINT "search failed" @ GOTO 3350 ELSE 3280
3280 ! one good reading
3290 F7=F1 @ F8=F9
3300 GOTO 3330
3310 ! two good readings
3320 F7=(F1+F2)/2 @ F8=ABS(F2-F1) ! average of two good readings
3330 ! final results
3340 PRINT USING 8510 ; F7,F8
3350 S4=1 ! fast refresh
3360 RETURN
3370 ! end:center freq mmt procedure=============================
```

```
3380 ! begin: Q measurement procedure==========================
3390 CLEAR @ DISP "Q measurement"
3400 DISP "center freq =";F7
3410 Q7=0
3420 PRINT USING 8570 ; TIME,F7,Z0,S$
3430 GOSUB 4950 ! measure peak voltage  v8  at f7
3440 A7=V8/V1
3450 ! set search limits
3460 F9=CEIL(F7/R7)
3470 F4=MAX(0,F7-20*F9)
3480 F5=F7+20*F9
3490 DISP "peak :";1000*A7*V1
3500 A4=A7*.707106781185 ! 1/2 power amplitude
3510 DISP "half power:";1000*A4*V1
3520 ! begin:search for lower 1/2 point
3530 F6=IP(F7)
3540 A8=A7
3550 ! begin :loop to find f6<f1
3560 F6=F6-F9
3570 IF F6>F4 THEN GOSUB 6990 ELSE 4090 ! xmtr on, or exit
3580 GOSUB 7310 ! measure A2
3590 DISP "q ";(A2-A4)*1000*V1
3600 ! check for downhill motion
3610 IF A2>A8 THEN 3620 ELSE 3650
3620 ! uphill; low 1/2 pt obscured
3630 PRINT USING 8520 ; F6,A2,A8 @ COPY
3640 GOTO 4110
3650 ! downhill-reset check val
3660 A8=A2
3670 IF A2<=A4 THEN 3680 ELSE 3550
3680 ! end loop
3690 ! begin loop: bracket 1/2 point
3700 IF F6<F7 THEN F6=F6+1 @ GOSUB 6990 ELSE 4090
3710 A8=A2 ! save last sample
3720 GOSUB 7310 ! new sample a2
3730 DISP "q!";(A2-A4)*1000*V1
3740 IF A2>=A4 THEN 3750 ELSE 3690
3750 ! end loop.bracketed -interpolate
3760 F1=F6-(A2-A4)/(A2-A8)
3770 PRINT USING 8530 ; F1
3780 ! end search for F1
```

```
3790 ! begin: search for hi 1/2 power pt F2
3800 F6=IP(F7)
3810 A8=A7 ! check value
3820 ! begin: loop for f6>f2
3830 F6=F6+F9
3840 IF F6<F5 THEN GOSUB 6990 ELSE 4090
3850 GOSUB 7310 ! measure A2
3860 DISP "q ";(A2-A4)*1000*V1
3870 ! check downhill motion
3880 IF A2>A8 THEN 3890 ELSE 3920
3890 ! uphill-hi 1/2 obscured
3900 PRINT USING 8520 ; F6,A2,A8 @ COPY
3910 GOTO 4110
3920 ! downhill-reset check val
3930 A8=A2
3940 IF A2<=A4 THEN 3950 ELSE 3820
3950 ! end loop
3960 ! begin loop. bracket 1/2 point
3970 IF F6>F7 THEN F6=F6-1 @ GOSUB 6990 ELSE 4090
3980 A8=A2 ! save last sample
3990 GOSUB 7310 ! new sample a2
4000 DISP "q!";(A2-A4)*1000*V1
4010 IF A2>=A4 THEN 4020 ELSE 3960
4020 ! end loop.bracketed-interpolate
4030 F2=F6+(A2-A4)/(A2-A8)
4040 PRINT USING 8540 ; F2
4050 Q7=F7/(F2-F1) ! quality factor
4060 S4=1 ! fast refresh
4070 PRINT USING 8550 ; Q7
4080 S4=1 ! fast refresh
4090 RETURN
4100 ! begin:error processing
4110 PRINT USING 8560 ; F6
4120 COPY
4130 GOTO 4080
4140 ! end:Q measurement procedure==============================
```

```
4150 ! begin: wavelength measurement procedure==================
4160 CLEAR @ DISP "min/max positioner"
4170 IF S5 THEN V6=V3 ELSE V6=V4 ! select T or P drive
4180 F6=F7 @ T7=T8 @ GOSUB 6990 ! xmtr on,long delay
4190 GOSUB 7310 ! warmup read
4200 IF S3 THEN S9=2 @ GOSUB 5770 ! plot start, a vs z
4210 DISP "position=";Z0
4220 DISP "stepsize";@ INPUT Z9
4230 PRINT USING 8720 ; TIME,Z0,Z9
4240 ! begin:initialize sample array
4250 FOR I2=1 TO 7
4260 GOSUB 7310 ! read amplitude A2
4270 Z4=Z0 @ GOSUB 7610 ! move down z9 mm
4280 Z(I2)=Z4 @ A(I2)=A2
4290 NEXT I2
4300 ! end: initialize array
4310 S7=0
4320 ! begin: search loop
4330 Z4=Z(4) ! array center
4340 !  parabolic fit
4350 U2=(5*(A(7)+A(1))-3*(A(5)+A(3))-4*A(4))/84
4360 U1=(3*(A(7)-A(1))+2*(A(6)-A(2))+(A(5)-A(3)))/28
4370 U0=(7*A(4)+6*(A(5)+A(3))+3*(A(6)+A(2))-2*(A(7)+A(1)))/21
4380 U9=Z8 @ X0=Z4 @ A7=U0-U1*U1/(4*U2)
4390 Z2=Z4-Z8*U1/(2*U2) ! predicted optimum
4400 DISP USING 8660 ; Z4,Z2,U1,U2
4410 IF S7 OR ABS(Z2-Z4)<R5*Z9 THEN 4420 ELSE 4460
4420 ! hit- document
4430 IF S7 THEN 4550 ! end search
4440 S7=1 ! set search end
4450 Z3=Z2 ! save peak estimate
4460 ! continue search
4470 ! push down sample array
4480 FOR I0=1 TO 6
4490 Z(I0)=Z(I0+1) @ A(I0)=A(I0+1)
4500 NEXT I0
4510 GOSUB 7310 ! read a2(z0)
4520 Z(7)=Z0 @ A(7)=A2
4530 IF S7 THEN PRINT USING 8730 ; Z2,1000*A7*V1,U1,U2 ELSE GOSUB
 7610
4540 GOTO 4320
4550 ! end: search loop
```

```
4560 ! print final estimate
4570 PRINT USING 8730 ; Z2,1000*A7*V1,U1,U2
4580 Z2=(Z2+Z3)/2 ! average
4590 PRINT "average=";Z2;"mm"
4600 IF S3 THEN GOSUB 5830 ! show plot
4610 ! begin data review
4620 IF S6 THEN 4630 ELSE 4640
4630 IF S5 THEN V3=V6 ELSE V4=V6 ! store ADC results
4640 DISP CHR$(11);"/4 count=";N9+2;@ INPUT W$
4650 IF LEN(W$)>0 THEN 4660 ELSE N9=N9+2 @ GOTO 4680
4660 W0=VAL(W$)
4670 IF W0>0 THEN N9=W0 ELSE 4910
4680 ! begin:accept measurement
4690 I9=I9+1
4700 W1,L9=Z2/1000 ! meters
4710 ! begin: sums
4720 C1=C1+N9 ! ~x
4730 C2=C2+N9*N9 ! ~x^2
4740 C3=C3+L9 ! ~y
4750 C4=C4+N9*L9 ! ~xy
4760 C5=C5+L9*L9 ! ~y^2
4770 C6=I9*C2-C1*C1 ! del factor
4780 ! end: sums
4790 ! begin:compute sound spd
4800 IF C6>0 THEN 4810 ELSE 4870
4810 ! two points or more
4820 W1=(I9*C4-C1*C3)/C6 ! slope
4830 W0=(C2*C3-C1*C4)/C6 ! intercept
4840 C7=4*W1*F7
4850 IF I9>2 THEN 4860 ELSE 4870
4860 C8=4*SQR((C5+I9*W0*W0+W1*W1*C2-2*W0*C3-2*W1*C4+2*W0*W1*C1)/(
I9-2)*I9/C6)*F7
4870 ! document
4880 PRINT USING 3690 ; I9,C7,C8,1000*W1
4890 GOTO 4930
4900 ! end : accept measuremt
4910 ! begin: discard measuremt
4920 PRINT "mmt discarded"
4930 S4=1 @ RETURN
4940 ! end: wavelength measurement procedure====================
```

```
4950 ! begin: 5-pt peak voltage   measurement procedure========
4960 IF S5 THEN V6=V3 ELSE V6=V4 ! select T or P drive
4970 F6=F7 @ T7=T8 @ GOSUB 6990 ! xmtr on ,long delay
4980 GOSUB 7310 ! warmup read
4990 ! begin:five-point mmt of peak amplitude v2
5000 S0=S6 @ S6=0 ! ADC off
5010 F6=F7-2 @ GOSUB 6990 ! set xmtr Fn-2
5020 GOSUB 7310 ! read v2(Fn-2);1st term
5030 F6=F6+1 @ GOSUB 6990 ! xmtr on Fn-1
5040 V8=-(3*V2/35) ! first term
5050 GOSUB 7310 ! read at Fn-1
5060 F6=F6+1 @ GOSUB 6990 ! xmtr on Fn
5070 V8=V8+12*V2/35 ! 2d term
5080 GOSUB 7310 ! read at Fn
5090 F6=F6+1 @ GOSUB 6990 ! xmtr on Fn+1
5100 V8=V8+17*V2/35 ! center term
5110 GOSUB 7310 ! read at Fn+1
5120 F6=F6+1 @ GOSUB 6990 ! xmtr on Fn+2
5130 V8=V8+12*V2/35 ! 4th term
5140 GOSUB 7310 ! read at Fn+2
5150 V8=V8-3*V2/35 ! result at f7
5160 S6=S0 ! restore ADC
5170 RETURN
5180 ! end: peak voltage   mmt================================
```

```
5190 ! begin: calibrate hydrophone procedure===================
5200 W1=C7/F7 ! wavelength
5210 H1=FNH(PI*D5/W1) ! length average corrn for T
5220 H2=FNH(PI*D6/W1) ! length average corrn for H
5230 PRINT USING 8700 ; A$,FNL(H1),FNL(H2)
5240 ! begin:preamp calibration
5250 CLEAR @ DISP "calibration"
5260 I8=4 @ GOSUB 8120 ! switch
5270 DISP "preamp calibrate" @ WAIT T8*3
5280 F6=F7 @ V6=V5*G8/G2 @ T7=T8 @ GOSUB 6990 ! xmtr on
5290 GOSUB 7310 ! read LIA out
5300 G2=G7*A2
5310 PRINT USING 8740 ; FNL(G2),1000*V1
5320 ! end: preamp calibration
5330 ! T}H measurements
5340 I8=3 @ GOSUB 8120 ! switch
5350 DISP "T}H" @ INPUT W$
5360 GOSUB 4950 ! 5-pt mmt of v8
5370 E3=V8*H2/G2 ! Eth
5380 J3=V1*2*PI*F7*Y3 ! amperes
5390 PRINT USING 8750 ; V1,1000*J3,1000000*E3
5400 ! end T}H
5410 ! begin P}H
5420 I8=-2 @ GOSUB 8120
5430 DISP "P}H" @ INPUT W$
5440 ! P drive adjust
5450 F6=F7 @ V6=V4 @ T7=T8 @ GOSUB 6990 ! xmtr on
5460 GOSUB 7310 ! warmup reading
5470 ! begin: adjust loop
5480 GOSUB 6990 ! xmtr on
5490 GOSUB 7310 @ E2=V2*H2/G2 ! read v2, correct for preamp
5500 DISP USING 8710 ; 1000*V6,1000*V2/G2,1000000*E3
5510 IF ABS(E2-E3)>R3*E3 THEN V6=FNR(V6*E3/E2) @ GOTO 5470
5520 ! end  adjust loop
5530 V4=V6
5540 PRINT "P drive:";V4;"V"
5550 ! end : P drive adjust
5560 GOSUB 4950 ! v8 mmt
5570 E2=V8*H2/G2 ! Eph
5580 PRINT " Eph=";1000000*E2:"uV"
5590 ! end P}H
```

```
5600 ! begin P>T
5610 DISP "P>T" @ I8=-1 @ GOSUB 8120 ! switch
5620 GOSUB 4950 ! v8 mmt
5630 E1=V8*H1/G2 ! Ept
5640 PRINT " Ept =";1000000*E1;"uV"
5650 ! end P>T mmts
5660 ! begin sensitivity calc
5670 J7=PI*D3*F7/(K0*C7*C7*Q7)
5680 PRINT USING 8760 ; F7,C7,Q7
5690 PRINT USING 8770 ; D3,K0,J7
5700 M1=SQR(J7*E1*E3/(E2*J3))
5710 M2=SQR(J7*E2*E3/(E1*J3))
5720 PRINT USING 8780 ; FNM(M1),FNM(M2)
5730 ! end sensitivity comp
5740 S4=1 @ RETURN
5750 ! end:calibrate phones====================================
```

```
5760 ! ========PLOT PROCS========
5770 ! begin: plot initialize procedure==========================
5780 DISP "load plotter";@ INPUT W$ ! dummy input
5790 IF LEN(W$)>0 THEN S3=0 @ RETURN ! abort plot
5800 PEN 1 @ FRAME @ PENUP
5810 RETURN
5820 ! end: plot initialize procedure==========================
5830 ! begin: show  plot procedure===========================
5840 ! begin: scaling
5850 B1,B4=99999 @ B2,B5=-B1
5860 FOR I0=1 TO I3
5870 W0=X(I0) @ W1=Y(I0)
5880 IF W0>B2 THEN B2=W0
5890 IF W0<B1 THEN B1=W0
5900 IF W1>B5 THEN B5=W1
5910 IF W1<B4 THEN B4=W1
5920 NEXT I0
5930 DISP "data range x:";B1;B2
5940 DISP "           y:";B4;B5
5950 ! X axis scale
5960 B3=5 ! x-interval
5970 W0=5*B3 ! major divisions
5980 B8=(CEIL(B2/W0)-IP(B1/W0))*5
5990 IF B8>50 THEN 6010 ELSE 6000
6000 IF B8<20 THEN 6080 ELSE 6160
6010 ! too many divisions
6020 K3=1
6030 B3=B3*B(K3) @ K3=FNK(K3)
6040 W0=5*B3
6050 B8=(CEIL(B2/W0)-IP(B1/W0))*5
6060 IF B8>50 THEN 6030 ELSE 6160
6070 ! end too many divisions
6080 ! begin too few divisions
6090 K3=3
6100 B3=B3/B(K3) @ K3=FNK(K3)
6110 IF B3>0 THEN 6120 ELSE 6200
6120 W0=5*B3
6130 B8=(CEIL(B2/W0)-IP(B1/W0))*5
6140 IF B8<20 THEN 6100 ELSE 6160
6150 ! end too few divisions
6160 ! end if
6170 B1=IP(B1/W0)*W0 ! low x bdry
6180 B2=B1+B3*B8 ! hi x bdry
6190 GOTO 6250
6200 ! method failed-set default  x scaling
6210 B3=(B2-B1)/10
6220 B8=10
```

```
6230 DISP "default x-scaling"
6240 ! end default scaling
6250 ! end x scaling
6260 ! begin y scaling
6270 B6=.002 ! mV
6280 W2=5*B6
6290 B9=(CEIL(B5/W2)-IP(B4/W2))*5
6300 IF B9>40 THEN 6320 ELSE 6310
6310 IF B9<10 THEN 6380 ELSE 6450
6320 ! begin too many divisions
6330 K3=3
6340 B6=B6*B(K3) @ W2=5*B6 @ K3=FNK(K3)
6350 B9=(CEIL(B5/W2)-IP(B4/W2))*5
6360 IF B9>40 THEN 6340 ELSE 6450
6370 ! end too many divisions
6380 ! begin too few  divisions
6390 K3=1
6400 B6=B6/B(K3) @ W2=5*B6 @ K3=FNK(K3)
6410 IF B6>0 THEN 6420 ELSE 6490
6420 B9=(CEIL(B5/W2)-IP(B4/W2))*5
6430 IF B9<10 THEN 6400 ELSE 6450
6440 ! end too few  divisions
6450 ! end if
6460 B4=IP(B4/W2)*W2
6470 B5=B4+B6*B9 ! hi y bdry
6480 GOTO 6540
6490 ! method fail-set default y-scaling
6500 B6=(B5-B4)/10
6510 B9=10
6520 DISP "default y-scaling"
6530 ! end default y scaling
6540 ! end y-scaling
6550 SCALE B1,B2,B4,B5
6560 ! end scaling
6570 ! plot points
6580 OUTPUT 705 ;"SMo;"
6590 K3=I3-7
6600 IF K3<1 THEN K3=0 @ GOTO 6640
6610 FOR I0=1 TO K3
6620 PLOT X(I0),Y(I0),0
6630 NEXT I0
6640 OUTPUT 705 ;"SM+;"
6650 K3=K3+1
6660 FOR I0=K3 TO I3
6670 PLOT X(I0),Y(I0),0
6680 NEXT I0
6690 OUTPUT 705 ;"SM;"
6700 CSIZE 4 @ FXD 1,3
```

```
6710 LAXES B3,B6,B1,B4,5,5
6720 N4=N4+1 @ H$=A$[33,37] @ PRINT "plot ";H$;"#";N4
6730 SETGU
6740 MOVE 0,62 @ LDIR 90 @ LORG 6
6750 LABEL USING "K" ; "amplitude(mV rms)"
6760 LDIR 0 @ LORG 4 @ MOVE 72,12
6770 IF S9=2 THEN W$="depth(mm)" ELSE W$="frequency(Hz)"
6780 LABEL USING "K" ; W$
6790 MOVE 72,5 @ CSIZE 5
6800 IF S9=2 THEN LABEL USING 8670 ; F6,S$,H$,N4 ELSE LABEL USING
 8680 ; Z0,S$,H$,N4
6810 SETUU @ PENUP
6820 ! end: point plot
6830 ! begin: curve fit plot
6840 B3=(B2-B1)/100
6850 FOR W1=B1 TO B2 STEP B3
6860 W2=W1-X0
6870 W3=1000*V1*(U0+U1*W2/U9+U2*(W2*W2)/(U9*U9))
6880 IF W3>B4 AND W3<B5 THEN PLOT W1,W3
6890 NEXT W1
6900 PENUP
6910 MOVE 0,0 @ PEN 0
6920 ! end: curve fit plot
6930 ! begin: clear plot
6940 I3=0 @ S9=0
6950 ! end: clear plot
6960 RETURN
6970 ! end:  plot procedure==============================
```

```
6980 ! ======MEASUREMENT PROCEDURES=============================
6990 ! begin: amplitude read setup procedure==================
7000 ! input:S6,F6,V6  out: timer #1 set for read enable, read en
able s1 off
7010 IF S6 THEN 7020 ELSE 7250
7020 ! begin: ADC block
7030 ! automatic drive adjust
7040 OUTPUT 707 USING 8800 ; V6,F6 ! HP3314 drive on
7050 S1=0 @ ON TIMER# 1,T7+I5*T5 GOSUB 7550 ! read disable
7060 ! begin: loop to adjust V6 until LIA output is in limits
7070 WAIT 2*T5
7080 ENTER 709 ; A5 ! read LIA magnitude-ignore read disable
7090 IF A5>.8 THEN 7100 ELSE 7130
7100 ! LIA out too high
7110 IF A5>1.12 THEN V6=FNR(V6*.5) ELSE V6=FNR(V6*.7)
7120 GOTO 7170
7130 IF A5<.1 THEN 7150 ELSE 7290 ! here's the loop exit point!
7140 ! LIA out too low
7150 V6=MIN(10,FNR(V6*15))
7160 GOTO 7170
7170 ! reset HP3314 and retest
7180 OUTPUT 707 USING 8810 ; V6
7190 OFF TIMER# 1 @ S1=0
7200 ON TIMER# 1,T8+(I5-2)*T5 GOSUB 7550
7210 PRINT S$[1,1];" drive";V6;"V"
7220 ! hold for read enable
7230 IF S1 THEN 7060 ELSE 7220
7240 ! end: ADC block
7250 ! begin: no ADC block
7260 OUTPUT 707 USING 8800 ; V6,F6
7270 S1=0 @ ON TIMER# 1,T7+I5*T5 GOSUB 7550 ! read disable
7280 ! end:no ADC block
7290 T7=0 @ RETURN
7300 ! end: amplitude read setup procedure ====================
```

```
7310 ! begin:amplitude read procedure==========================
7320 ! in:S1,V0 out: v2,a2
7330 ! hold for read enable
7340 IF S1 THEN 7350 ELSE 7330
7350 ! read enable
7360 TRIGGER 723 ! measure xmtr voltage
7370 ENTER 709 ; A5 ! LIA magnitude output
7380 V2=A5*V5 ! volts receiver   output
7390 ENTER 723 ; V1 ! xmtr voltage
7400 A2=V2/V1
7410 ! check for LIA overload
7420 IF A5>1 THEN 7430 ELSE 7450
7430 ! alarm -overload
7440 PRINT "LIA OVERLOAD" @ PRINT F6;A5;V1 @ BEEP 55,2000
7450 ! end: overload test
7460 DISP USING 8580 ; F6,Z0,1000*V1,1000*V2
7470 IF S3 AND S9 AND I3<50 THEN 7480 ELSE 7530
7480 ! graphics storage
7490 I3=I3+1
7500 IF S9=2 THEN X(I3)=Z0 ELSE X(I3)=F6
7510 Y(I3)=1000*V2 ! mV
7520 ! end graphics storage
7530 RETURN
7540 ! end : amplitude read procedure==========================
7550 ! begin:read enable procedure=============================
7560 ! called by timer#1-resets read enable flag s1
7570 OFF TIMER# 1
7580 S1=1
7590 RETURN
7600 ! end: read enable procedure==============================
```

```
7610 ! begin: move manipulator down Z9 mm========================
7620 ! input: z9
7630 ENTER 720 ; N0 ! counter ref
7640 IF ABS(Z9)<.5 THEN 7680
7650 IF Z9>0 THEN OUTPUT 709 ;"CLS1" @ N3=1 ELSE OUTPUT 709 ;"CLS
0" @ N3=-1 @ Z9=-(Z9/R8)
7660 ON TIMER# 2,IP(Z9/R2-T2) GOSUB 7700 ! set stop time
7670 S1,S2=0 ! read off,inmotion
7680 RETURN
7690 ! end: move manipulator procedure==========================
7700 ! begin: manipulator stop procedure========================
7710 ! input z0,z9,n0,n3
7720 ! output revised z0,step z8
7730 IF N3>0 THEN OUTPUT 709 ;"OPN1" ELSE OUTPUT 709 ;"OPN0"
7740 OFF TIMER# 2
7750 ENTER 720 ; N1
7760 ! loop until ctr stops
7770 ENTER 720 ; N2
7780 IF N2=N1 THEN 7790 ELSE N1=N2 @ GOTO 7760
7790 ! motion stop
7800 Z8=N3*(N1-N0)/R0
7810 Z0=Z0+Z8
7820 DISP USING 8790 ; Z0,Z8
7830 S2=0 ! flag motion stop
7840 ! auto drive control
7850 IF S6 THEN 7860 ELSE 7950
7860 ! begin:adjust drive
7870 ENTER 709 ; A5
7880 IF A5>.95 THEN 7890 ELSE 7950
7890 ! LIA out too high
7900 IF A5>1.12 THEN V6=FNR(V6*.5) ELSE V6=FNR(V6*.7)
7910 OUTPUT 707 USING 8810 ; V6
7920 PRINT "drive:";V6;"V"
7930 WAIT I5*T5+T8
7940 GOTO 7870
7950 ON TIMER# 1,T7+I5*T5 GOSUB 7550 ! set delay to read enable
7960 T7=0
7970 RETURN
7980 ! end:manipulator stop procedure===========================
7990 ! begin: manipulator relocate procedure====================
8000 CLEAR
8010 IF Z0=0 THEN DISP "position";@ INPUT Z0
8020 DISP "move to";@ INPUT Z4
8030 Z9=Z4-Z0 ! mm
8040 GOSUB 7610 ! move z9 mm
8050 S4=1 @ RETURN
8060 ! end: manipulator relocate procedure======================
```

```
8070 ! begin: title string justifier============================
8080 I0=LEN(A$)
8090 IF I0 MOD 32>0 THEN A$=A$&" " @ GOTO 8080
8100 RETURN
8110 ! end title justifier==================================
8120 ! ADC/xmtr toggle routine=============================
8130 IF I8=0 THEN 8140 ELSE 8170
8140 ! operator call
8150 S4=1 ! fast refresh menu
8160 CLEAR @ DISP "1=P}T 2=P}H 3=T}H 4=cal";@ INPUT I8
8170 ! process command
8180 IF I8>0 THEN S6=1 ELSE S6=0 @ I8=-I8 ! I8>0 turns ADC on
8190 I8=I8 MOD 5
8200 IF I8=0 THEN 8420
8210 OUTPUT 707 ;"APOVO"
8220 ON I8 GOTO 8230,8280,8330,8380
8230 ! P}T
8240 S5=0 @ S$="P}T"
8250 OUTPUT 706 USING 8820 ; "B1A1"
8260 OUTPUT 714 USING 8820 ; "B2A2"
8270 GOTO 8420
8280 ! P}H
8290 S5=0 @ S$="P}H"
8300 OUTPUT 706 USING 8820 ; "B2A1"
8310 OUTPUT 714 USING 8820 ; "B2A2"
8320 GOTO 8420
8330 ! T}H
8340 S5=1 @ S$="T}H"
8350 OUTPUT 706 USING 8820 ; "B2A2" !
8360 OUTPUT 714 USING 8820 ; "B3A3"
8370 GOTO 8420
8380 ! preamp calibration
8390 S5=0 @ S$="P}cal"
8400 OUTPUT 706 USING 8820 ; "B3A1"
8410 OUTPUT 714 USING 8820 ; "B3A1"
8420 PRINT USING "/K/" ; S$
8430 I8=0 @ RETURN
8440 ! end: xmtr/adc toggle routine==========================
```

```
8450 ! Images for formatted output==============================
8460 IMAGE /////K
8470 IMAGE //"time:",6D/"center freq measurement"/"estimate:",5D/
"range:",3D/"stepsize:",3D/
8480 IMAGE #,"*",4D,2X,S.4DE
8490 IMAGE #,8D.2D
8500 IMAGE /"peak:",5D.2D,"Hz"/5X3D.5D,"mV"/5XS.3DE,"mV/Hz^2"/"xm
tr:",K,"mV"
8510 IMAGE /"resonance center frequency"/5D.2D,"+/-",2D.3D,"Hz"
8520 IMAGE /"1/2 power pt obscured"/4D,2(XK)
8530 IMAGE "low 1/2:",5D.D
8540 IMAGE "high 1/2:",5D.D
8550 IMAGE "resonance quality factor:",2D.2D
8560 IMAGE /"search limit exceeded",5D
8570 IMAGE /"time:",6D/"Q measurement"/"center freq:",5D.2D/"dept
h",4D.D/ K /
8580 IMAGE "o",4D,X4D.D,6D.2D,3D.5D
8590 IMAGE /K/"Fn=",K,"+/-",2D.2D/"Cn=",K,"+/-",2D.2D/"Qn=",K/"M(
T)=",K,"dB"/"M(H)=",K,"dB"
8600 IMAGE /"0=return to main 1=LIA"/"2=water          3=drive","
4=comments          5=constants"
8610 IMAGE "lockin analyzer"/"input ",X2D.4D,"mV"/"expand",X3D/"t
ime ",X5D,"x",2D,"+",X5D,"ms"
8620 IMAGE "depth(mm):",K/"volume(m^3):",D.6D
8630 IMAGE K/"T length=",K,"mm"/"capacitance=",K,"pF"/"H length="
,K,"mm"/
8640 IMAGE "water temperature"/2D.D," C"
8650 IMAGE "6=title          7=plot on/off"/"8=position        9=
dcr specs"
8660 IMAGE "^",4D.2D,2XK/" ",2(XS.3DE)
8670 IMAGE 4D,"Hz ",K,7X,K,"#",2D
8680 IMAGE 3D.D,"mm ",K,6X,K,"#",2D
8690 IMAGE /2D," pts"/"spd=",4D.2D,"+/-",2D.2D,"m/s"/"=",K,"mm"
8700 IMAGE K/"T corrn:",S2D.2D,"dB"/"H corrn:",S2D.2D,"dB"/
8710 IMAGE "pda",3D.2D,2(X.4DE)
8720 IMAGE /"time:",6D," max/min locator"/"start:",4D.D," step:",
3D.D/
8730 IMAGE "min/max:",4D.D,"mm"/8X3D.5D,"mV"/"slope:",S.4DE/"curv
:",S.3DE/
8740 IMAGE "preamp gain:",3D.2D,"dB  @ ",K,"mV"
8750 IMAGE " Vt=",K,"V"/" It=",K,"mA"/" Eth=",K,"uV"
8760 IMAGE //"freq:",5D.2D/"sound spd:",4D.2D/"Q:",3D.3D
8770 IMAGE "volume:",K/"density:",4D.2D/"Jn:",K/
8780 IMAGE "T:",4D.2D,"dB re 1V/uPa"/"H:",4D.2D,"dB re 1V/uPa"//
8790 IMAGE "stop:",4D.2D,5D.4D
8800 IMAGE "AF",2D.5D,"VO FR",4D,"HZ"
8810 IMAGE "AF",2D.5D,"VO"
```

```
8820 IMAGE #,4A
8830 ! end: images==============================================
8840 ! begin: end program routine===============================
8850 OUTPUT 709 ;"RS"
8860 OUTPUT 707 ;"APOVO"
8870 END
```

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